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University of Michigan Studies

SCIENTIFIC SERIES

VOLUME IV

THE GLACIAL ANTICYCLONES: THE POLES OF THE ATMOSPHERIC CIRCULATION

THE MACMILLAN COMPANY
NEW YORK BOSTON CHICAGO
ATLANTA SAN FRANCISCO

MACMILLAN & CO., LIMITED
LONDON BOMBAY CALCUTTA
MELBOURNE

THE MACMILLAN CO. OF CANADA, LTD
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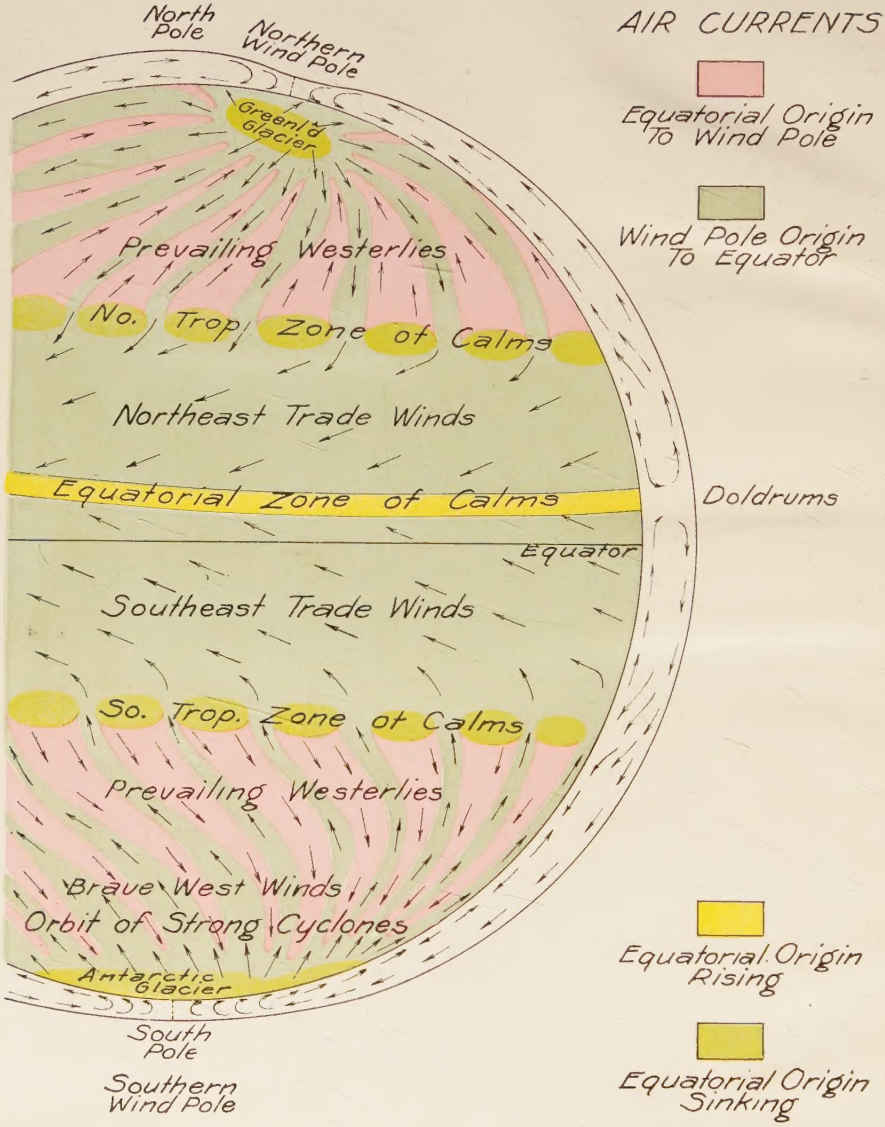
PLATE I



MAP OF THE EASTERN PART OF THE WESTERN HEMISPHERE TO SHOW THE SCHEME OF ATMOSPHERIC CIRCULATION (see Chapter X)

THE GLACIAL ANTICYCLONES

THE POLES OF THE ATMOSPHERIC CIRCULATION

BY

WILLIAM HERBERT HOBBS

UNIVERSITY OF MICHIGAN

WITH AN INTRODUCTION

BY

HUGH ROBERT MILL

LATELY PRESIDENT OF THE

ROYAL METEOROLOGICAL SOCIETY

New York

THE MACMILLAN COMPANY

London: Macmillan & Company, Limited

1926

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Set up and printed,
April, 1926

PRINTED IN THE UNITED STATES OF AMERICA

To the Memory

OF

ROBERT EDWIN PEARY

GREATEST OF ALL SLEDGING EXPLORERS AND
DISCOVERER OF THE LAW OF THE SLOPE
WINDS ON THE INLAND-ICE OF GREENLAND

INTRODUCTION

The polar regions remained blank on the map of the world while the foundations of the geo-physical sciences were being laid, and the few series of observations in the Arctic region gathered during the nineteenth century had little influence on the theories of atmospheric circulation in which the senior men of science of today were brought up. Thus it is natural that conceptions of the system of planetary circulation in the atmosphere should have hardened into a form generally accepted as orthodox in which more weight was given to the part played by tropical than by polar regions in maintaining the great movements on which the climates of the world depend. It is perhaps not too much to say that the polar regions as factors in atmospheric movements came to be viewed by meteorologists as inert areas containing the poles, round which a symmetrical circulation was assumed to take place in the direction required by a theory in the formation of which no polar phenonema, except polarity, had been considered. This was a sort of involuntary blindness to the absence of data; for of course it was perfectly well known that the intensity of air movements depends ultimately, not on the high temperature of the tropics, but on the difference of temperature between the tropics and the polar regions.

It happened that in all the successive theories of world wind circulation put forward by Maury, Ferrel and James Thomson, the polar regions were assumed to be areas of low sea-level atmospheric pressure fed by inflowing winds showing a symmetrical cyclonic circulation round the pole. In the case of the Antarctic regions this conclusion was possible only by ignoring

the observations made in high southern latitudes by Cook, Bellingshausen, Biscoe, Ross, Wilkes and Dumont d'Urville, so heavily did the intellectual inertia of an unsupported theory weigh all unconsciously on the minds of men of science. Even now the tradition of an old belief has not died out, and it is curious to note how slowly physical geographers came to recognize the truth of the absolutely consistent observations by which the Antarctic explorers of the twentieth century confirmed the observations and contradicted the theoretical conclusions of the nineteenth. Eventually the detailed results of the simultaneous and successive Antarctic expeditions of 1901 to 1914 made it necessary to modify the old theory so as to admit the new facts of extremely low temperatures and outflowing winds from the high interior of the Antarctic Continent. Even then great ingenuity was exercised in the endeavor to stretch and patch the old skins of theory to enable them to hold the new wine of discovery.

It was during this transition period that Professor Hobbs, leaving old theory aside and starting afresh from ascertained facts, produced his theory of the glacial anticyclone as an active cause of wind formation and a powerful element of planetary wind circulation. It was natural and perfectly right that meteorologists should receive the new suggestion in a critical spirit, and no doubt its author preferred a reception which put him on his mettle to defend his theory by proving its competence to absorb new facts, for knowledge is advanced to greater purpose by a process of vigorous attack and defence than by passive acceptance of untested hypotheses.

Since the theory of the glacial anticyclone was first stated, a large amount of new material has been made available from both polar areas, and in this monograph to which Professor Hobbs has asked me to write an Introduction, which I feel to be wholly unnecessary, he has discussed afresh the whole array of facts,

new and old, and restated his theory with the enthusiastic thoroughness characteristic of all his work.

As a meteorologist and a student of the polar regions, I have been deeply impressed by the way in which he has marshalled the facts and deduced conclusions which must arrest the attention of meteorologists and physicists. Whether this theory is accepted or assailed it cannot fail to be recognized as a courageous attempt to bring newly discovered phenomena into relation with previously existing knowledge. So far as I can test the theory, it seems to me to be fundamentally sound and even though more competent critics may prove it to require amendment or extension, it must remain a notable step in advance.

The theory involves the principle that the increase of the density of air resting on a downward-sloping, solid surface by the continuous withdrawal of heat is as potent a means of maintaining circulation as is the reduction of density of air resting on an upward sloping land surface by the continuous addition of heat. The principle has long been familiar on a small scale in the case of the down-hill night winds and the up-hill day winds of mountain valleys. The novelty consists in its application to wide regions where refrigeration is practically continuous at all hours and in all seasons, so that the interplay is not local and intermittent but widespread and uninterrupted. The outflowing surface wind on all sides should produce a descent of air from the upper regions, which must be supplied from the outside and convey with it the moisture necessary to nourish the snowfields.

Meteorologists feel a theoretical difficulty as to the maintenance of an ice-cap under a permanent system of descending and therefore dry air, and Professor Hobbs meets this objection to the essential part of his theory by an appeal to facts. He shows that all explorers have found the central area of the glacial anticyclone in Antarctica and in Greenland to be a region

not of dry air but of high relative humidity with frequent fogs or falls of ice-spicules. He sees in the cirrus clouds an adequate source of supply for this moisture and adduces well-thought-out reasons for his view. As there is no evidence of the permanent wasting of the snow-covering, it is obvious that the clouds contain moisture brought from outside. Such an influx is provided for in Professor Hobbs' conception of the glacial anticyclone, though to most meteorologists the fact of air being drawn in to a central area argues the existence of a cyclonic system. Unless both sides adopt the same terminology verbal agreement is of course hopeless.

That Professor Hobbs is a geologist whose glacialogical studies have compelled him to apply himself to meteorology adds to the interest and value of his work. He approached the specific problem with a mind free from that faintest cloud of prejudice or tradition which sometimes may befog the most honest specialist who has toiled long in building up the fabric of his science. This clear unbiased outlook lends a crisp freshness to the discussion which is truly inspiring. The acknowledged insufficiency of existing observations for the complete elucidation of the phenomena dealt with is likely to stimulate the ambition of young investigators who combine a love for science with the human thirst for adventure. The field of exploration is the most remote and difficult in the world, as only Greenland and the Antarctic Continent present an expanse of lofty snow-covered land sufficient to provide down-rushes of cold air capable of affecting the general circulation of the atmosphere. The view has often been expressed in recent years that the key to atmospheric circulation is to be found in the Antarctic; but Greenland may by its position near some of the most powerful " centres of action " in the Northern Hemisphere prove no less important in an area which although smaller, exerts vastly more influence on all the activities of human life. The records of some of the

recent Antarctic expeditions have not yet been made available, but with these exceptions all the data required to complete the aërological study of Antarctica and Greenland must be obtained by special expeditions for the launching of which scientific research alone can furnish the motive. I hope that this investigation by Professor Hobbs may prove the starting point of a new period of purely scientific polar research freed from the distressing accompaniments of pole-hunting and the making of sensational cinema films.

It may not be inappropriate to caution readers, and in particular critics, of this monograph that they should bear in mind the definitions used by the author in his discussion. I am by no means sure that the expression glacial anticyclone is the happiest form of words to convey the idea of the atmospheric phenomena to which it applies, though I cannot suggest a better. The establishment of true relations between temperature, altitude, configuration of the land and air-flow in polar conditions is the one aim in view; the name by which it is called is a minor consideration. Some critics may have habituated themselves to view an anticyclone as a grouping of isobars representing pressure reduced to sea-level and accompanied by a surface windflow of definite direction and strength, an affair of two dimensions only. Others may view an anticyclone as a mass of air which for some reason is not taking part in the atmospheric circulation around it.

An anticyclone is usually considered in association with moving cyclones as an incident in the weather-producing turbulence of the great atmospheric currents. Sometimes the term "anticyclone" is applied to one of the more or less permanent belts or areas of high pressure which in conjunction with the zones of low pressure determine the prevailing winds of the globe. However justly the name may be applied in any or all of these cases, the reader must remember that Professor Hobbs uses the words Glacial Anticyclone as meaning a permanent and

complete circulatory system in a mass of air in three dimensions extending from the ground to the limit of the troposphere and including the indraught of air from a distance, as well as the downward and outward flow of air of the surface.

The investigation of the free atmosphere has recently been carried with much success to heights far above those reached by any land, and important deductions have been made as to the conditions governing vertical movements of air at high levels. The extent of the disturbance introduced into the theoretical conditions of free air at 10,000 feet by the intrusion of a mass of land sloping up from sea-level to that height has not yet been fully investigated; but it is clear that deductions from observations in the free air at 10,000 feet over the sea or low land, cannot be expected to hold good for air resting on a surface of ice at that altitude. In such studies isotherms and isobars reduced to their probable values at sea-level are very uncertain guides, and even professional meteorologists have to go warily lest they outrun the facts of observation which no theory can contradict and live.

The reader who approaches the subject with an open mind will, I am sure, find Professor Hobbs as clear and convincing in his statement of facts as he is stimulating and suggestive in the development of his well-supported theory.

HUGH ROBERT MILL

October 19, 1925

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The Glacial Anticyclones: The Poles of the Atmospheric Circulation

CHAPTER I

THE THEORY STATED

ITS HISTORY

Outline of 1911. — "As regards their physiographic form the inland-ice masses adhere to a definite model — a flat dome which in the case of the Antarctic example is extended by a lower marginal terrace of shelf ice.

"Inland-ice . . . appears to be regularly fed from *high-level* currents through the operation of a refrigerating air engine of which the ice mass and its atmospheric cover are the essential parts.

"Through the rhythmic action of this engine the congealed moisture derived from the ocean surface within moderate or low latitudes and carried to the polar region in the high-level cirrus

Note. — Portions of this monograph have been read in abstract before various scientific societies. A paper entitled "The Glacial Anticyclone" was presented in Section E at the Toronto Meeting of the British Association for the Advancement of Science, August 9, 1924; and one entitled "The Source of the Cold Air of the North 'Polar Front'" was read in the same Section at the Southampton Meeting, August 28, 1925 (*Nature*, vol. 116, No. 2918, October 3, 1925, pp. 519–521). A paper entitled "L'Asymetrie de la Circulation atmosphérique" (*Comptes Rendus de l'Academie des Sciences*, t. 181, 17 août, 1925, pp. 289–290), was presented before the Academy of Sciences, Paris, on August 17, 1925; and one entitled "The Place of Greenland in the Earth's Atmospheric Circulation" before the Danish Geological Society at Copenhagen on September 7, 1925. On November 19, 1925, an address on "The Poles of the Atmospheric Circulation" was delivered in Washington before a joint meeting of the Washington Academy of Sciences and the Geological Society of Washington.

clouds, is pulled down to the surface of the glacier in the eye of a great glacial anticyclone which is centred above it. During their descent from high levels the ice grains of the clouds are melted and vaporized by adiabatic warming, and on reaching the cold surface layer of air next the ice, are quickly congealed to form flakes of fresh snow. The progressive warming of the air adia-

FIG. 1. Ideal.zed section across inland-ice (from *Characteristics of Existing Glaciers,* 1911)

batically both during its descent to the central area of the ice mass and on the further slide outward to the peripheral portions, gradually damps and eventually stops the sliding centrifugal motion of the surface air-layer. Thus the engine comes to rest or, as we may say, has reached the end of its stroke. The great calm which ensues allows heat to be again slowly abstracted from the surface layer of air, thereby lowering its temperature and raising its density until gravity again starts the engine, which now acquires the steadily accelerating velocity characteristic of bodies sliding on inclined planes. The tempest which is eventually engendered is succeeded by a rapid rise of air temperature, a fall of fresh snow, and another stopping of the engine.

" The fierce violence of the surface air currents when at their maximum, and the fall of the snow for the most part as the

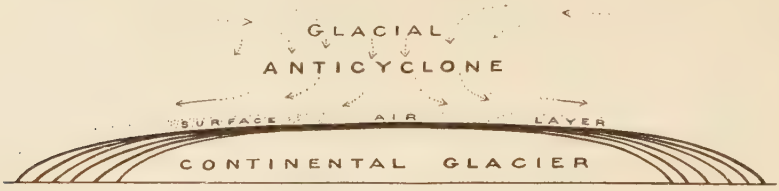

FIG. 2. Diagram to illustrate the growth of an inland-ice mass through the rhythmic action of the anticyclonic air engine (from *Characteristics of Existing Glaciers,* 1911)

engine is slowing down, together make of this glacial anticyclone a gigantic snow broom. The snow deposited as it were between strokes of the engine is by the next sweep of the broom brushed largely clear from all central portions [1] of the glacier, and the sweepings are deposited near and about the margins of the mass" (see Fig. 2).

First statement of the theory. — The theory of the glacial anticyclone was first stated by the writer in the year 1910 in two monographs entitled, "Characteristics of the Inland-ice of the Arctic Regions," and "The Ice Masses on and about the Antarctic Continent;" which appeared respectively in the *Proceedings of the American Philosophical Society* in Philadelphia and in the *Zeitschrift für Gletscherkunde* at Vienna. With revision and additions these monographs comprise Parts II and III of *Characteristics of Existing Glaciers,* which was published by the Macmillan Company in 1911, from the Afterword of which volume the opening paragraphs of this monograph are taken. The approach to the subject of the anticyclone was first made, therefore, from the standpoint of the study of continental glaciers, and not from that of the meteorologist. Throughout, the inquiry has been pursued not with a view to determine upon the basis of certain principles assumed to be true what *ought* in nature to occur; but, rather, from actual observation to find out what *is,* and upon this foundation to seek a simple and adequate explanation.

In these original papers, moreover, the theory of the glacial anticyclone was arrived at from a survey of all observational data then available from explorations on and about the world's two great continental glaciers — the study was made throughout from original sources. The place of this fixed anticyclone in the

[1] This statement is too comprehensive, as we know today. The reading should be *large areas of the higher slopes* rather than "all central portions" of "the glacier."

economy of continental glaciers was vital, for it accounts for their nourishment and growth and the fashioning of their surfaces, as well as for their wastage and eventual gradual disappearance.

The supplementary data from the second period. — Close upon the appearance of these monographs sketching in broad lines the glacial anticyclone, there opened the second, and by far the most important, of the periods of exploration both in Greenland and in the Antarctic — a period of between three and four years which supplied of really essential scientific facts more than had been acquired in all preceding time. Some matters which had before been "seen through a glass darkly" came out in the clear light of day. It was a matter of special gratification, therefore, to find that the newly derived material added confirmation from new localities and along new lines, of the correctness of the picture already sketched in *Characteristics of Existing Glaciers* of the glacial anticyclone as a mechanism.

To assemble from the scattered and sometimes difficultly accessible sources this wealth of new material, and to give it its proper place in the fuller description of the glacial anticyclone, a new monograph was prepared and published in 1915; this time, however, not as a work dealing primarily with glaciers, but as an investigation of an essential though unrecognized feature of the earth's general atmospheric circulation. This monograph was entitled, "The Rôle of the Glacial Anticyclone in the Air Circulation of the Globe." [2]

New material to be correlated. — Since the appearance of the later monograph many final reports of earlier Greenlandic and Antarctic explorations have been issued which contain fuller data than had before been available; several important new explorations have been made; and now, after more than a decade has elapsed, the time seems ripe for issuing another monograph which

[2] *Proc. Am. Phil. Soc.*, vol. 54, pp. 185–225, 11 figs.

shall not alone bring the whole subject up to date with some discussion of the views now held, but which shall in addition serve to correct some misunderstanding which has arisen. For a wide misapprehension among those meteorologists and climatologists who treat their subjects largely from the standpoint of mathematics, there is a simple explanation to be found in the history of the evolution of thought concerning the polar regions. This can be made clear only by a discussion of the history of exploration within the polar regions and of the methods which have rather generally been employed by meteorologists in making use of the data. Such, then, is the plan which it is proposed to follow. In addition to the author's monographs mentioned above, many smaller papers dealing with some phase of the subject of the glacial anticyclone have from time to time been issued.[3]

[3] W. H. Hobbs, "The Ice Masses on and about the Antarctic Continent, "*Zeitsch. f. Gletscherk,* vol. 5, 1910, pp. 36–122; "Characteristics of the Inland-ice of the Arctic Regions," *Proc. Am. Phil. Soc.,* vol. 49, 1910, pp. 57–129; *Characteristics of Existing Glaciers,* Macmillan, 1911, Chaps. IX and XVI, and especially the Afterword; "The Pleistocene Glaciation of North America Viewed in the Light of our Knowledge of Existing Continental Glaciers," *Bull. Am. Geogr. Soc.,* vol. 43, 1911, pp. 641–659; *Earth Features and Their Meaning,* Macmillan, 1912, pp. 283–286; "The Rôle of the Glacial Anticyclone in the Air Circulation of the Globe," *Proc. Am. Phil. Soc.,* vol. 54, 1915, pp. 185–225, figs. 11 (reviewed in *Meteorologische Zeitschrift,* Jahrg. 33, 1916, pp. 79–80J); "The Ferrel Doctrine of Polar Calms and its Disproof in Recent Observations," *Proc. Second Pan-American Scientific Congress,* vol. 2, Sec. II, Washington, 1917, pp. 179–189; "The Mechanics of the Glacial Anticyclone Illustrated by Experiment," *Nature,* London, July 22, 1920; "The Fixed Glacial Anticyclone Compared to the Migrating Anticyclone," *Proc. Am. Phil. Soc.,* vol. 60, 1921, pp. 34–42; "Les Characteristiques des Glaciers Continentaux Comparées a Celles des Glaciers de Montagne," traduit par J. Blache [Conference faite a l'université de Grenoble le 1er mai, 1922], *Revue de Geogr. Alpine,* vol. 10, 1922, pp. 81–89.

CHAPTER II

EARLY VIEWS CONCERNING CIRCULATION ABOUT THE POLES

EARLY EVIDENCE FROM THE SOUTHERN SEAS LONG SUPPOSED TO INDICATE LOW ATMOSPHERIC PRESSURE ABOUT THE POLES

During the late thirties and early forties of the last century three great national exploring expeditions visited the Antarctic region. The first to set out were a fleet comprising the American expedition commanded by Lieutenant, later Commodore, Charles Wilkes and the French expedition in two vessels under the command of Admiral Dumont d'Urville; these expeditions covered the period 1838–43. An English expedition in the ships *Erebus* and *Terror* was commanded by Sir James Clark Ross and covered the years 1839–43. All of these expeditions discovered the Antarctic Continent buried in snow and ice, but no one of them succeeded in setting foot upon it. Their scientific results apply directly, therefore, to the seas only, and not to the continent. In common they brought out a most important difference which obtains between Arctic and Antarctic sea conditions in the neighborhood of the land, though one which has received scant consideration. Whereas in the north polar area fogs are prevalent, close to the Antarctic Continent the weather was found to be generally clear.

Wilkes, 1842, 1851. — Wilkes skirted the Antarctic Continent, enveloped as it is in attached and floating ice-masses, keeping near the latitude of the Antarctic Circle. For many hundreds of miles within the Australian quadrant he cruised in the general vicinity of this border. His meteorological log shows for

most of the distance rather low barometric pressures, but the winds blew strongly off the continent, bringing with them a clear sky though with much snow carried in the air.[1] If corrections in the course of the coast line be made upon the basis of Mawson's recent exploration, the dominance of off-shore winds in the neighborhood of the continent becomes even more striking (Fig. 3).[2]

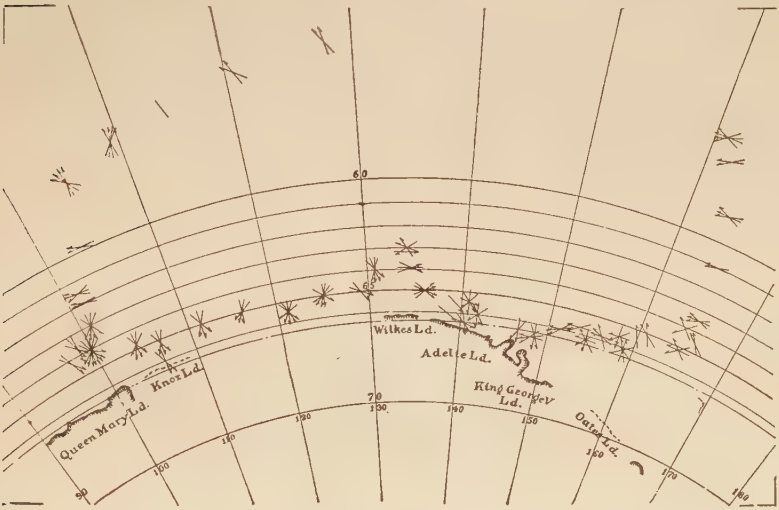

FIG. 3. Map of a portion of the Antarctic near which the wind directions recorded in the log of Wilkes have been plotted. Near Adelie Land the coast line has been corrected to accord with Mawson's map. The arrows point to the wind quarter.

D'Urville, 1841–45. — The French exploring expedition encountered similar weather conditions when in the neighborhood of

[1] Charles Wilkes, *Synopsis of the Cruise of the U. S. Exploring Expedition during the Years 1838, 1839, 1840 and 1841,* Washington, 1842, pp. 22–23; *Narrative of the United States Exploring Expedition during the Years 1838, 1839, 1840, 1841, 1842,* vol. 2, Phila., 1844, Chapters IX–XI. U. S. Exploring Expedition, Comm. Chas. Wilkes, Phila., 1851, vol. 11, pp. xxxi and 303.

[2] Cf. Hobbs, *Proc. Am. Phil. Soc.*, vol. 54, 1915, p. 216, fig. 8.

the Antarctic Continent and the same low pressures of the barometer.[3] What has been more generally overlooked by meteorologists is that when very close to the Antarctic Continent D'Urville refers again and again in his narrative to the east and southeast winds which replace the usual "brave west winds." In a footnote he says:

> This continual east wind in high latitudes is very remarkable. It is well known that, between the 30th and 68th parallels, the prevailing wind is almost constantly from the west. It is not impossible that beyond this limit the east wind becomes more frequent than the west. We do not yet know anything of the meteorological observations made in the same latitudes by Captains Wilkes and James Ross; but the routes followed by these navigators in their exploration of the polar regions seem as if they should lead to the same conclusions.[4]

Ross, 1847. — Like Wilkes and D'Urville, Sir James Ross encountered low atmospheric pressures in the far southern seas, and over the Ross Sea was found an apparently permanent cyclone with excessively low pressures. Yet like most other Antarctic explorers he found at the very margins of the continent a rise of pressure and winds from the southerly and southeasterly quarters.[5] His meteorological data were fully discussed in a publication of the Meteorological Office.[6]

Maury, 1855. — The great influence upon meteorological theories of *The Physical Geography of the Sea*,[7] by Matthew Fontaine Maury, it is now difficult to understand unless one has in mind that it was written at a time when clipper sailing ships

[3] J. S. C. Dumont d'Urville, *Voyage au Pôle Sud et dans l'Oceanie, etc., Histoire du Voyage,* 23 vols., atlas, Paris, 1841–45.

[4] Cited from the translation of D'Urville's narrative printed in *The Antarctic Manual,* p. 475.

[5] James Clark Ross, *A Voyage of Discovery and Research in the Southern and Antarctic Regions during the Years 1839–43,* 2 vols., London, 1847.

[6] *Contributions to our Knowledge of the Meteorology of the Antarctic Regions,* 1873.

[7] M. F. Maury, *The Physical Geography of the Sea,* 5th edition, 1855, pp. 78–79.

were competing for the China trade and when there was the most intense rivalry between Great Britain and the United States.[8] Any new and trustworthy information with regard to prevailing route winds or ocean currents was at once seized upon with avidity. Based as it was upon Maury's famous *Wind and Current Charts,* the *Physical Geography of the Sea* had a prestige quite without parallel and passed through twenty-two editions between 1855 and 1860. Maury believed that these observations of navigators indicated a low-pressure area surrounding the poles with westerly winds blowing home to the poles.

Buchan, 1889. — In 1889 Buchan, who wrote the meteorological reports of the *Challenger* expedition, brought out his now classical series of meteorological charts of the world. In explanation of them he said:

> Perhaps the most remarkable region of low pressure is in the Antarctic region, which remaining low throughout the year, plays the principal rôle in the wind systems bordering on and within the Antarctic circle. . . . It is probable that over nearly the whole of the Antarctic region mean pressure is at least less than 29.85 inches.[9]

EVIDENCE FROM NEAR THE BORDERS OF THE ANTARCTIC CONTINENT INDICATES A HIGH PRESSURE AREA

Allusion has already been made to the neglected observations of navigators when south of 60° south latitude. These observations are strikingly accordant in indicating winds from a southerly and rather generally also an easterly quarter, and hence in

[8] See William Brown Meloney, *The Heritage of Tyre,* Macmillan, N. Y., 1916, pp. 180.

[9] Buchan later changed his views and accepted gracefully and very promptly the results of observation. See, for example, his discussion of Donald's data where he said, "the experience of Mr. Bruce and Dr. Donald, who found south, south-east, and east winds prevailing in these regions, seemed to indicate that the South, like the North Pole was situated in the midst of an anticyclonic area." (*Scot. Geogr. Mag.,* vol. 10, 1894, p. 68).

contrast with the "brave west winds" encountered between the fortieth and sixtieth parallels — the "roaring forties" and "screeching fifties." For reasons hard to discover these observations have been quite largely either overlooked or set aside by meteorologists generally.

Neumayer, 1872. — In 1872 Georg Neumayer published the results of extended study of Antarctic voyages, giving his attention more especially to the drift of the floating sea-ice as indication of winds and currents.[10] He maintained that the "brave west winds" did not extend south of the 60th parallel of latitude. He says:

> It should be especially noted here that, south of the 60th parallel of latitude, in the Austral summer, easterly and south-easterly winds prevail, which, towards the end of the season, frequently blow severe storms.

Bruce, 1894. — W. S. Bruce, later to become internationally known as the leader of the Scottish expeditions to the Antarctic, as early as 1892 and 1893 went to the Antarctic as naturalist upon a whaling vessel and brought back some of the best meteorological data which up to that time had been secured. In his report he said:

> Like our predecessors, we found it [the Antarctic Region] to be a region of gales and calms — gales from the north, with wet fog; gales from the south, with blinding snow; calms with fog, and calms with brilliant sunshine.

Of one of these gales he says:

> For ten hours we steamed as hard as we could against it, and at the end had only made one knot.[11]

A summer gale from the south for the most part, but with the wind shifting to south-southeast and south by east, Bruce estimated to have a force of 10.

[10] G. Neumayer, "Die Erforschung des Süd-Polar-Gebietes" (with map), *Zeitsch. Gesell. f. Erdkunde,* vol. 7, 1872, pp. 120–170; "Exploration of the South-polar Regions," *Nature,* vol. 7, 1872, pp. 21–23, 62–66, 138–140.

[11] W. S. Bruce, "Antarctic Exploration," *Scot. Geogr. Mag.,* vol. 10, 1894, pp. 60–61. See also *The Antarctic Journal,* London, 1909, pp. 35–38.

Murray, 1894. — In a paper read before the Royal Geographical Society, Sir John Murray wrote in summary as early as 1894:

> All the teaching of meteorology therefore indicates that a large anticyclone with a higher pressure than prevails over the open ocean to northwards overspreads the Antarctic continent. While this anticyclonic region may not be characterized by an absolutely high pressure at all seasons, it must be high relatively to the very low pressure which prevails to the northward.[12]

Fricker, 1898. — Another writer who saw clearly the bearing of the observations which had so far been made at the borders of the Antarctic Continent was Karl Fricker, who in his *Antarktis,* published at Berlin in 1898, said:

> We are compelled then to assume that over the Antarctic land itself barometric high pressure constantly prevails, corresponding to the unbroken low temperature, and from this region radiate those southern winds, which owing to the axial motion of the earth are diverted to the left and become south-east winds.[13]

But here the shade of Ferrel makes its appearance, for he continues:

> How to harmonize the circumpolar anticyclone deduced from these observations with the *cyclone demanded by theory* [italics not in the original], is a question still involved in obscurity, and the solution of this problem must be left to future explorers. . . .

Arctowski, 1900. — The *Belgica* expedition of 1898–99 drifted in the pack-ice of the South American quadrant of the Antarctic, largely between the parallels of 65° and 70°. The expedition was fortunate in having a very competent meteorologist, Dr. Henryk Arctowski, who as early as 1900 supplied in an Appendix to a popular account of the expedition, a summary of the meteorology of the region within which the ship drifted. Arctowski wrote:

[12] John Murray, *Geogr. Journ.,* vol. 3, 1894, p. 17. Reprinted in *Smith. Report for 1893* (1894), p. 365.

[13] Karl Fricker, *Antarktis,* Scholl and Grund, 1898, p. 187; *The Antarctic Regions* (translation by A Sonnenschein), London, 1900, p. 240.

Every time the wind blew from the north the temperature rose, even in midwinter, to 0°, but it did not ascend higher. As soon as the wind shifted and blew from the south the thermometer descended abruptly, even in the middle of summer, to a very low temperature.

In the interior of the antarctic continent there must be a pole whose temperature is much lower than the frigidity of the arctic poles of cold; the frozen surface of the antarctic continent is in effect much larger than that of Greenland, Northern Siberia or North America. The zone explored by the *Belgica* lies in a cyclonic region; yet the mean barometric pressure of the year, 744 mm. 7, obtained by a direct observation, is superior by 6 mm. to the theoretical figure obtained by Ferrel for that latitude, and demonstrates that the pressure does not decrease progressively toward the pole, where, on the contrary, there must reign an anticyclone.[14]

Elsewhere Arctowski says:

I am of opinion that the great Graham Land peninsula forms an anticyclonic region, . . . Victoria Land being, in all likelihood, equally a region of high pressure.[15]

Bernacchi, 1901. — The first exploring expedition to make a landing upon the Antarctic Continent, and this succeeded only in exploring the area of a few square miles, was the *Southern Cross* expedition, which was sent out near the opening of the new century by Sir George Newnes and commanded by Borchgrevink. The meteorologist of this expedition was Louis Bernacchi, who on the basis of systematic meteorological observations supplied cogent arguments for the existence of an anticyclone centered over the continent. For the eleven months of his stay on the continental border, he found that the prevailing winds continually blew outward and from the southeasterly quadrant only, whereas the high-level cirrus clouds invariably moved inward from the opposite quadrant.[16]

[14] Frederick A. Cook, *Through the First Antarctic Night,* Doubleday & McClure Co., New York, 1900, p. 415.

[15] H. Arctowski, "The Antarctic Voyage of the 'Belgica' during the Years 1897, 1898, and 1899," *Smith. Misc. Coll. for 1901–1902,* p. 385 (reprint from *Geogr. Journ.,* Oct., 1901).

[16] L. Bernacchi, *To the South Polar Regions,* London, 1901, pp. 300–302.

THE DOCTRINE OF "CIRCUMPOLAR CYCLONES" AND "POLAR CALMS"

Maury, 1855–60. — In 1855, a year in advance of the classical paper by Ferrel on atmospheric circulation, there appeared Maury's *Physical Geography of the Sea.* Of the polar winds Maury said:

> Operated upon by the equilibrating tendency of the atmosphere and by diurnal rotation, the wind approaches the north pole, for example, by a series of spirals from the southwest. If we draw a circle about this pole on a common terrestrial globe, and intersect it by spirals to represent the direction of the wind, we shall see that the wind enters all parts of this circle from the southwest, and, consequently, that a whirl ought to be created thereby, in which the ascending column of air revolves from right to left, or *against* the hands of a watch. At the south pole the winds come from the northwest . . . , and consequently there they revolve about it with the hands of the watch.[17]

Except that the air within the polar regions is considered to be ascending, we find already in this treatise by Maury the notion of the polar calms of Ferrel, who treated the subject mathematically in an obscure paper published during the following year. Surface winds blowing inward in spirals from either the southwest or northwest toward the poles, and there rising and flowing outward at higher levels, is the conception which Maury offered. How he arrived at this conception, he makes clear in the eighth edition of his treatise, which was published in 1860. On the basis of observations made by navigators between the parallels of 40° and 54° south latitude, the average barometer reading varies, he states, from 29.9 to 29.4 in passing from the lower to the higher latitude. With the gradient derived from this limited range of 14° of latitude, Maury *extended the curve as a straight line through thirty-six degrees of latitude to obtain for the South Pole a theoretical value of 28 inches* (711 mm., (Fig. 4).

[17] M. F. Maury, *The Physical Geography of the Sea,* 5th ed., 1855, pp. 78–79.

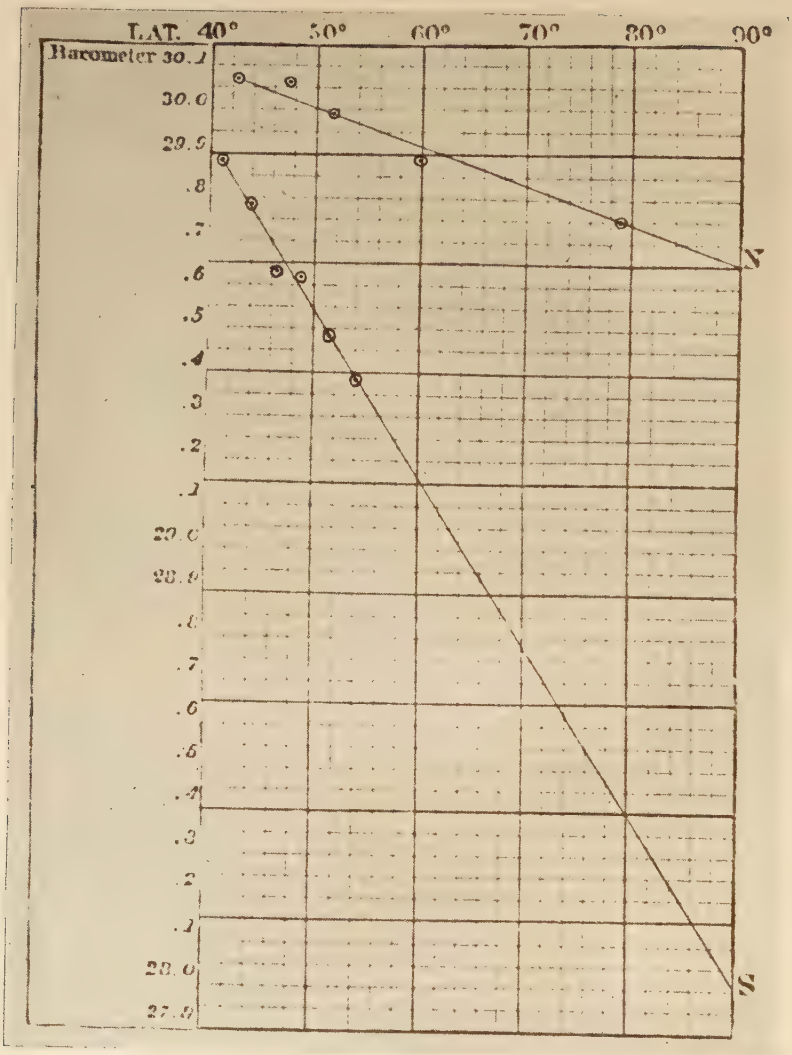

FIG. 4. Diagram from which Maury derived the extreme low pressure about the South Pole, the basis of his own and Ferrel's belief that the polar regions are both areas of low atmospheric pressure (after Maury)

In the last (twenty-second) edition of his treatise, Maury wrote:

> . . . the air which these vapor-bearing winds — vapor-bearing because they blow over such an immense tract of ocean — pour into this stopping-place has to ascend and flow off as an upper current, to make room for that which is continually flowing in below. In ascending it expands and grows cool, and, as it grows cool, condensation of its vapors commences; with this, vast quantity of latent heat, which converted the water out at sea into vapor for these winds, are set free in the upper air. There it reacts by warming the ascending columns, causing them still further to expand, and so to rise higher and higher, while the barometer sinks lower and lower. This reasoning is suggested not only by the fact and circumstances already stated as well known, but it derives additional plausibility for correctness by the low barometer of these regions (Fig. 4).[18]

It must be clear that Maury with all his knowledge of navigator's logs has here gone strangely astray; for not only did Wilkes, D'Urville and Ross find southeasterly winds the rule south of the 61st parallel, but the earlier navigators of the Antarctic gave much prominence to their difficulties in fighting their way southward against contrary winds at the higher latitudes. The statements of Maury cited above are not found in his earlier editions, and it is evident that Maury here drew on Ferrel, who in turn had to a marked degree been under the influence of Maury's early editions in forming his theory of the polar cyclones and calms.

Of the Antarctic Maury wrote:

> . . . as, in every system of aerial circulation there must be some point or place at which motion ceases to be direct and commences to be retrograde, so there must be a place somewhere on the surface of our planet where these winds cease to go forward, stop, and commence their return to the north; *and that place is, in all probability, within the antarctic regions* [italics in the original]. Its precise locality has not been determined, but I suppose it to be a band or disc — an area — within the polar circle, which, could it be explored, would be found, like the equatorial calm belt, a place of light airs and calms, of ascending columns of air, a region of clouds, of variable winds, and constant precipitation[19] (Fig. 5).

[18] M. F. Maury, *The Physical Geography of the Sea and its Meteorology,* twenty-second edition, being the eighth edition of the author's reconstruction of the work, London, 1860, p. 447.

[19] *Op. cit.,* pp. 446–447.

Referring to the "brave west winds" between the 40th and the 60th parallels of south latitude. Maury says:

> . . . we may contemplate the whole system of these "brave west winds" in the light of an everlasting cyclone on a gigantic scale. The antarctic continent is in its vortex, about which the wind in the great atmospherical ocean all around the world, from the pole to the edge of the calm belt of Capricorn, is revolving in spiral curves, continually going with the hands of a watch, and twisting from left to right.[20]

FIG. 5. Maury's diagram to illustrate his view of the general atmospheric circulation (after Maury, 1855)

Ferrel, 1856, 1858, 1889. — The treatise upon the winds by another American, William Ferrel, has long been regarded as a classic, and justly so. Ferrel's first discussion of the subject

[20] *Op. cit.*, p. 449.

appeared in 1856. As he tells us in the introduction to his *Popular Treatise on the Winds* he was much under the influence of Maury's work above cited,[21] from which he learned "that the pressure of the atmosphere is less both at the poles and at the equator of the earth than it is over two belts extending around the globe about the parallels of 30° north and south of the equator." In this his first full discussion of atmospheric circulation, but by no means including the clearest statement of his views, Ferrel described polar calms near the polar circles with the air motions within these belts coming from the west. He says further (*Prof. Pap. Sig. Serv.*, No. XII, No. 2, pp. 24–25):

> Near the poles the tendency to flow towards the equator seems to be greater, and causes a current there *from* the poles, which, being deflected westward . . . , causes a slight northeast wind in the north frigid zone and a southeast wind in the south frigid zone; but this is only near the earth's surface, and the general tendency of the atmosphere in the upper regions must be towards the east as will be seen.
>
> . . . Near the polar circles, where the polar and passage-winds meet, there must also be calm belts, which may be called polar calm belts.
>
> That the atmosphere is depressed at the equator and the poles . . . is indicated by barometrical pressure. It was formerly thought that this pressure at the level of the ocean, was very nearly 30 inches in all latitudes; but it is now well established that it is much less towards the poles than near the tropics. . . .

It is evident that Ferrel based his belief that low pressures of the atmosphere had been observed about the poles upon Maury's diagram (see Fig. 4) in which extrapolation had been carried through thirty-six degrees of latitude over an unexplored region; for he makes the following amazing reference to

[21] W. Ferrel, "The Motions of Fluids and Solids on the Earth's Surface," originally published in *Rinkle's Mathematical Monthly* between 1858 and 1860, and republished in *Prof. Papers of the Signal Service*, U. S. War Dept., No. VIII, 1882, pp. 5–51; "The Motions of Fluids and Solids Relative to the Earth's Surface," *ibid.*, No. XII, 1882, pp. 21–34 (reprinted from *Am. Journ. Sci.*), (2) vol. 31, pp. 27–51; *A Popular Treatise on the Winds*, 1889, pp. 505.

the "*observed low barometer of the polar regions,*" and no such observations existed or exist today. He says:

> In none of the treatises on meteorology or physical geography is there to be found any satisfactory explanation of the observed low barometer in the polar regions. . . . Observations show that in the antarctic region there is a permanent depression of more than one inch below the average height nearer the equator, and in the arctic region a depression of about half that amount; . . .[22]

Ferrel's scheme of atmospheric circulation underwent important changes in his own hands as regards conditions within the horse latitudes (see Fig. 6). In respect to the polar region, with which we are especially concerned, the original view of Ferrel was not changed essentially, and until 1920 it had been the generally accepted view of meteorologists (see the sequel, Chap. X). In his latest writing upon this subject Ferrel said: [23]

> There is, therefore, a depression of the isobaric surfaces at all altitudes in the polar regions, especially in the southern hemispheres, . . . but at high altitudes there is a minimum of barometric pressure at the poles and a maximum at the equator. . . .
>
> The polar depression of the isobaric surfaces is greater in the southern than in the northern hemisphere (pp. 155–156).

Again he says:

> . . . there is, at the earth's surface, an area of low pressure around each pole with its minimum at the pole . . . (p. 139).

Thus from Ferrel's own writings it is apparent that his polar whirls and calms, often referred to as the "polar cyclones," are not in reality cyclones at all, but they set forth a type of circulation never yet observed on land or sea. They are in reality half cyclone and half anticyclone. As regards the pressure of the atmosphere, the direction of rotation of the vortex and the indraft of the surface air, they partake of the nature of the cyclonic vortex; whereas in their assumption that the air de-

[22] William Ferrel, "The Cause of Low Barometer in the Polar Regions and in the Central Part of Cyclones," *Prof. Pap. Sig. Serv.*, U. S. War Dept., No. XII, 1882, p. 35.

[23] W. Ferrel, *A Popular Treatise on the Winds*, New York, 1889, pp. 505.

scends within the vortex, they are anticyclones. How this downdraft of air can be reconciled with low atmospheric pressures it is difficult to understand.

Later observations, especially those of Hildebrandsson and Teisserenc de Bort on the directions of motions of the upper

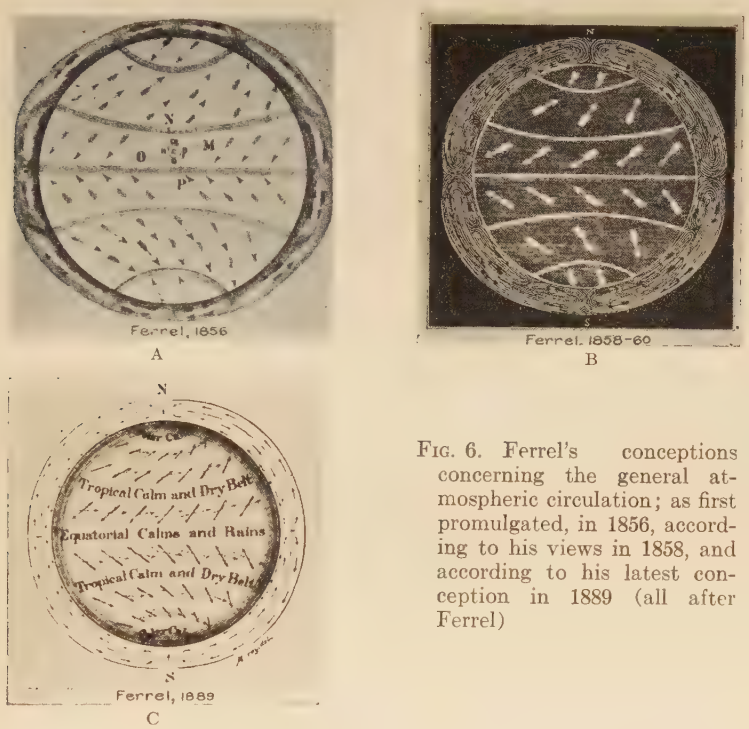

FIG. 6. Ferrel's conceptions concerning the general atmospheric circulation; as first promulgated, in 1856, according to his views in 1858, and according to his latest conception in 1889 (all after Ferrel)

clouds, have shown that Ferrel's earlier conceptions with regard to circulation of the air at the horse latitudes were the correct ones.[24]

[24] H. Hildebrand Hildebrandssen, "Résultats des recherches empiriques sur les mouvements généraux de l'atmosphère," *Nova Acta Reg. Soc. Scientiarum Upsaliensis*, Ser. IV, vol. 5, 1818, pp. 1–50, plates; H. H. Hildebrandsson et Teisserenc de Bort, *Les bases de la météorologie dynamique*, Paris, 1898, pp. 184.

J. Thomson, 1857. — James Thomson's theory of the atmospheric circulation was similar to Ferrel's, though worked out independently somewhat later and with much less thoroughness. As regards the polar regions, Thomson wrote:

> Thus it appears that, in temperate latitudes, there are three currents at different heights: — that the uppermost moves towards the pole, and is part of a grand primary circulation between equatorial and polar regions; — that the lowermost moves also towards the pole, but is only a thin stratum forming part of a secondary circulation; — that the middle current moves from the pole, and constitutes the return current from both the preceding; — and that all these three currents have a prevailing motion from west to east in advance of the earth.[25]

Von Helmholtz, 1888. — A quite novel conception was introduced into the discussion of the atmospheric circulation of the polar regions in 1888 by the distinguished physicist, Von Helmholtz. He focussed attention upon the effect of radiation from the cold earth's surface within high latitudes, which by increasing the density of the surface layer of air he believed would bring in more air from above and force a radial outward surface distribution. This theory, it will be observed, takes no account of the continental glaciers with respect to the amount of their radiation, and it does not consider the topography of the surface on which the atmosphere rests, but as a physical consequence it undoubtedly expresses conclusions of importance.[26] By meteorologists it had received slight consideration until 1920, when it was revived by Bjerknes as the basis of his " polar front " theory of atmospheric circulation (see Chapter X).

The views of meteorologists who have written upon this subject during the last two decades, or since the great periods of polar exploration began, will be discussed in the sequel.

Hann, 1897. — In his *Klimatologie* the late Professor Hann,

[25] James Thomson, " On the Grand Currents of Atmospheric Circulation," *Rept. Brit. Assoc. Adv. Sci.*, 1857, Pt. 2, pp. 38–39.

[26] H. von Helmholtz, " Ueber atmosphaerische Bewegungen," *Sitzungsb. d. k. pr. Akad. d. Wis.*, Jahrg. 1888, Demi-Bd. I, pp. 647–663.

of Vienna, generally regarded as the foremost meteorologist and climatologist of his time, wrote in 1897:

> The whole Antarctic circumpolar area presents us, as already stated, with a vast cyclone, of which the center is at the pole, while the Westerly winds circulate round it.[27]

[27] *Handbuch der Klimatologie,* 2te Aufl., vol. 3, 1897, p. 543.

CHAPTER III

THE ATMOSPHERIC PRESSURE OVER THE NORTH POLAR REGION

EVIDENCE THAT THIS PRESSURE IS NEITHER HIGH NOR LOW, BUT NORMAL

The polar sea. — Actual observations show that neither high nor low atmospheric pressure is characteristic of the north polar regions. In contrast with the south polar area, the solution of the question is here a relatively simple one, for the reason that instead of being a high dome of ice and snow, the north polar area is covered by a deep sea with floating ice-rafts whose surface nowhere rises more than a few tens of feet above the sea. This relatively level surface removes the necessity for correcting barometric readings for altitude where no satisfactory checks are to be had. For convenience we shall consider the north polar region to be the area surrounding the North Pole with a radius of about ten degrees.

For the greater part of three years (1894–96) Nansen slowly drifted on the *Fram* in a zigzag course within this region.[1] For convenience this period has here been divided into three sections so as to accord with the calendar years covered by the cruise, *viz.*: (1) January to December of 1894, within the sector bounded by the meridians of 140° and 100° E.; (2) January to December of 1895, within the sector bounded by the meridians of 100° and 45° E.; and, (3) the period from January to July of 1896, within the sector bounded by the meridians of 45° and 10° E. The first mentioned course of the *Fram* has an average latitude of

[1] *The Norwegian North Polar Expedition, 1893–96, Scientific Results,* edited by Fridtjof Nansen, vol. 6, London, 1905; *Meteorology,* by H. Mohn, pp. 659.

about 82° N., the second follows closely the parallel of 85° N., and the third, which covered a period of seven months, has a mean latitude of 83° N. The positions of these areas are indicated on the map of Figure 50 (p. 149).

For the complete year of 1895 when the *Fram* was nearest the pole and in a mean latitude of 85° N., the mean daily barometric reading was 761 mm. For the winter months (November to April inclusive) the mean was 764 mm., and for the summer months the figure was 758 mm. For the previous year when the *Fram* was somewhat further out from the pole and ranged in latitude from about 79° to 84° N., the mean daily barometric pressure was found to be 758 mm. For the winter months the mean was 756 mm., and for the summer months 760 mm. For the western area traversed in 1896 and having much the same range of latitude as that covered in 1894, but covering a period of seven months about equally divided between winter and summer, the value obtained for the barometric mean was 758 mm. In commenting upon the barometric pressures recorded by this expedition within these regions Mohn said: [2]

> The pressure at the North Pole seems to have its maximum, — about 764 mm. — in April, and minimum — 759 mm. — from June to September. This gives an annual range of only 5 mm.

Franz Josef Land. — We are in possession of systematic observations from several Arctic expeditions based on Cape Flora which is within this archipelago in latitude 79° 57′ N., and one at Teplitz Bay, Rudolph Island, in latitude 81° 47′ N. In the years 1899 to 1900 the expedition of the Duca degli Abruzzi spent twelve months at Cape Flora and found for the mean daily atmospheric pressure 760.3 mm. The mean for the month of January was 765.2 mm. and for the month of July, 762.1 mm.[3]

[2] *Op. cit.*, p. 572.

[3] S. A. R. Luigi Amedeo di Savoia, Duca degli Abruzzi, *Osservazioni scientifiche eseguite durante la spedizione polare, 1899–1900,* Hoepli, Milano, 1903, p. 396 and pl. VI.

At this same base of Cape Flora the Ziegler expedition spent fourteen months in 1904–5.[4] The annual mean of the daily atmospheric pressure was found to be 753.1 mm. For the winter months (November to April) the mean was 751.3 mm. and for the summer months 754.6 mm.

The Jackson expedition made its base at Cape Flora in the years 1904–6, and its observations of the barometer give for the mean annual pressure 756 mm. with but slight differences between the means of the summer and winter months.[5]

The Ziegler expedition for a period of seven months carried out systematic meteorological observations at Teplitz Bay on Rudolph Island in latitude 81° 47′ N. These were mainly the winter months — October to April inclusive. The mean daily reading of the barometer was 754.6 mm.[6]

Nansen on his return from the sledge journey towards the pole spent seven months in a hut in Northern Franz Josef Land in latitude 81° 13′ N. The mean barometer for these mainly winter months (October to April inclusive) was 757 mm.[7]

Northern coasts of Spitzbergen and Northeast Land. — Baron Adolf Erik Nordenskiöld on his polar expedition of 1872–73 spent two months at the base of Polhem and ten months at Mossel Bay in Northeast Land, both in latitude 79° 57′ N. The mean daily pressure at Mossel Bay was 757 mm., based on incomplete data. For the winter months based on complete data the figure was 756 mm.[8]

[4] A. Fiala, *The Ziegler Polar Expedition 1903–05,* William J. Peters, *Scientific Results,* published by the Nat. Geogr. Soc., Washington, D. C., 1907, p. 479.

[5] F. G. Jackson, *A Thousand Days in the Arctic,* 1899, App., p. 823.

[6] *Op. cit.,* p. 472.

[7] Nansen-Mohn, *op. cit.*

[8] Aug. Wijkander, *Observations Météorologiques de l'Expédition Arctique Suédoise, 1872–73,* Pt. 1, Kongl. Svenska Vetenskaps-Akademiens Handlingar, vol. 12, No. 7, Stockholm, 1875, 120 pages.

The German observatory established at Ebeltofthafen, Spitzbergen, in 1912 and 1913, carried out systematic meteorological observations for a period of thirteen months. The station was located in latitude 79° 9′ N., and the observations were made by Wegener and Robitzsch.[9] The mean pressure of the atmosphere for the period was 755.7 mm. For the winter months, November to April, the mean was 752.3 mm. and for the summer months 759.0 mm.

Northern coast of Grant Land. — Fort Conger near the northeast coast of Grant Land (Grinnell Land) in latitude 81° 40′ N. has been the base of several polar expeditions. The Greely expedition spent the years 1881–82 and 1882–83 at this station. The mean daily barometer reading for 1881–82 was 758 mm. and for 1882–83, 760 mm. Greely cites the earlier expedition of 1875–76 (Nares) which at the same base obtained the figure for mean atmospheric pressure of 759 mm. For the Hall expedition at Polaris Bay in the same latitude and across the strait for the year 1871–72 the corresponding figure, as cited by Greely, was 761 mm.[10]

Peary was in 1908–9 at Fort Conger for the seven months of December to June inclusive, and found for the mean barometric pressure 760 mm. At Cape Sheridan on the same coast but farther northwest and in the high latitude of 82° 25′ N. he obtained for a period of eight months (November to June inclusive) the mean barometric pressure of 760 mm.[11]

Recapitulation. — If now we summarize the values for mean

[9] Kurt Wegener und Max Robitzsch, "Klimatologische Terminbeobachtungen während der Ueberwinterung 1912–13," *Veröff. des Deutsch. Observatoriums Ebeltofthaven-Spitzbergen,* herausgegeben von H. Hergesell, Lindenberg, Vieveg, Braunschweig, 1916, pp. 8–33.

[10] Adolphus W. Greely, *Report on the Proceedings of the United States Expedition to Lady Franklin Bay, Grinnell Land,* vol. 2, Washington, D. C., 1888, pp. 154–156.

[11] R. E. Peary, *The North Pole,* 1910, App. 1 (R. A. Harris), pp. 346–348.

daily barometric pressure for areas surrounding the North Pole within a radius of approximately ten degrees and scattered through about three-quarters of the entire series of sectors we obtain the following figures:

Nansen,	1894	on polar sea in average	lat. 82°		758 mm.
Nansen,	1895	on polar sea in average	lat. 85°		761 mm.
Nansen,	1896	on polar sea in average	lat. 83°		758 mm.
D'Abruzzi,	1899–1900	Franz Josef Land	lat. 79°	77′	760 mm.
Fiala,	1904–5	Franz Josef Land	lat. 79°	77′	753 mm.
Jackson,	1904–6	Franz Josef Land	lat. 79°	77′	756 mm.
Fiala,	1904–5	Teplitz Bay, F.J.L.	lat. 81°	47′	754 mm.
Nansen,	1895–96	Rudolph I, F.J.L.	lat. 81°	13′	757 mm.
Nordenskiöld,	1872–93	Northeast Land	lat. 79°	57′	757 mm.
Wegener and Robitzsch,	1912–13	Advent Bay, Spitz.	lat. 79°	9′	756 mm.
Newnes,	1875–76	Fort Conger	lat. 81°	40′	759 mm.
Greely,	1881–82	Fort Conger	lat. 81°	40′	758 mm.
Greely,	1882–83	Fort Conger	lat. 81°	40′	760 mm.
Peary,	1908–9	Fort Conger	lat. 81°	40′	760 mm.
Hall,	1871–72	Polaris Bay	lat. 81°	40′	761 mm.
Peary,	1908–9	Cape Sheridan	lat. 82°	25′	760 mm.

It thus appears that the north polar area is one of strikingly normal barometric pressures with a slight tendency toward low rather than high pressure.

CHAPTER IV

THE BEGINNINGS OF EXPLORATION ON THE ANTARCTIC CONTINENT

THE FIRST GREAT PERIOD OF EXPLORATION

Concerted expeditions of 1901–4. — At the opening of the twentieth century several European countries took part in a concerted effort to establish stations upon the Antarctic Continent, from which stations explorations could be made, and at which regular meteorological and other scientific observations could be carried out at frequent stated periods in accordance with the practice of such stations in civilized countries so far as should be possible. Great Britain,[1] Sweden,[2] and Germany[3] entered into such an arrangement, and private enterprise was responsible for additional and in part simultaneous expeditions sent out to the Antarctic from France[4] and Scotland.[5]

[1] Robert H. Scott, *The Voyage of the "Discovery,"* 2 vols., London, 1905; "Results of the National Antarctic Expedition," *Geogr. Journ.*, vol. 25, 1905, pp. 353–392; *National Antarctic Expedition, 1901–1904, Meteorology,* Pt. I, London, 1908.

[2] O. Nordenskjöld, *Antarctica or Two Years amongst the Ice of the South Pole,* London, 1905; *Svenska Sydpolar Expeditionen 1901–1903,* Stockholm, 1910, Bd. 2, *Meteorologie* (Bodman).

[3] E. von Drygalski, *Zum Kontinent des eisigen Südens, Deutsche Südpolar-Expedition, Fahrten und Forschungen des "Gauss," 1901–1903,* Berlin, 1901, pp. 668; *Deutsche Südpolar-Expedition 1901 bis 1903,* III Bd., *Meteorologie,* I Bd., Berlin, 1911; W. Meinardus, "Die meteorologischen Ergebnisse der Deutschen Südpolar-Expedition 1902 bis 1903, II," *Meteor. Zeitsch.,* Bd. 28, 1911, Heft 8, pp. 346–349 (Referat von J. Hann).

[4] J. Charcot, *Le "Français" au Pôle Sud,* Flammarion, Paris, 1906, pp. 486.

[5] W. S. Bruce, "Some Results of the Scottish National Antarctic Expeditions," *Scot. Geogr. Mag.,* vol. 21, 1905, pp. 401–417; R. C. Mossman,

The rewards from the meteorological studies made at these Antarctic stations have been considerable, although far too much emphasis has been placed upon the correlation of the meteorological data thus obtained at remote stations located *outside* the continent, and too little regard has been paid to the very great influence exercised by essentially local conditions. In some instances these conditions take from the conclusions arrived at much of their supposed value. The old myth fostered by the conceptions in vogue concerning the general atmospheric circulation, has been responsible throughout for too great emphasis being placed upon latitude and too little upon the conditions regarding topography and radiation from the surface. The effect of topography generally and the importance of wind sluices near the stations, as we shall see, have been vouchsafed too little attention.

Hann's correspondence with Scott. — On the eve of the setting out upon these coöperative Antarctic expeditions a very interesting correspondence was carried on between Professor Hann at Vienna and Robert H. Scott, F.R.S., then head of the Meteorologic Office. Evidently much disconcerted by the observational data obtained by Bernacchi at Cape Adare in South Victoria Land, results which clearly indicated that an anticyclone, and not a cyclone, lay over the Antarctic Continent, Hann wrote:

> As regards the Antarctic Anticyclone I have certainly not expressed myself quite clearly in my "Klimatologie," as you very fairly point out.
>
> It is certain that an area of pressure, which is higher than that of the surrounding area, lying over a chilled continent, or over any considerable land area, can coexist with a great polar cyclone, for instance, round the South Pole. The very low temperature can produce in the lower strata of the atmosphere a pressure higher than its environment. *The anticyclone, however, must be very shallow, and at a moderate elevation the*

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ibid. pp. 417–429; Brown et al., *The Voyage of the "Scotia,"* Edinburgh and London, 1906, pp. 375. R. C. Mossman, "Meteorology," in W. S. Bruce, *Rept. on Scientific Results of the Voyage of the S. Y. "Scotia" during the Years 1902, 1903 and 1904,* Edinburgh, 1907, pp. 213.

ordinary circulation of the atmosphere must re-establish itself. . . . There is certainly no chance of the existence of a real continental anticyclone,[6] inasmuch as at Cape Adare the barometer falls from summer to winter.[7]

The weakness of the position here taken by Hann will be even more obvious in the sequel, for not only he but a large group of well-known meteorologists following his lead, took up a position of futile attempt to explain away new observations which were in opposition to speculations built into the structure of meteorology in such fashion that their abandonment involved a considerable rewriting of the subject.

Systematic observations on wind direction. — The best early summary which we have seen of the meteorological results of the concerted expeditions of 1901 to 1904 has been made by Professor Ward, the eminent American climatologist. His summary, it should be pointed out, relates primarily to the *station data:*

> Recent Antarctic exploration has considerably modified some of the views which have been held regarding the general winds of the south polar area and their controlling pressures. The rapid southward decrease of pressure, which is so marked a feature of the higher latitudes of the southern hemisphere on the isobaric charts of the world, does not continue all the way to the South Pole. Nor do the prevailing winds constituting the "circumpolar whirl," which are so well developed over the southern portion of the southern hemisphere oceans, blow all the way home to the South Pole. The steep poleward pressure gradients of these southern oceans end in a trough of low pressure, girdling the earth at about the Antarctic circle. From here the pressure increases again towards the South Pole, where a permanent inner polar anticyclone area is found, with outflowing winds deflected by the earth's rotation into easterly and southeasterly directions.[8]

Excellent as this statement is as setting forth the general bearing of the observations secured, it speaks in terms of the geographic poles and it is not entirely correct in its generalizations concerning the prevalence of easterly and southeasterly

[6] Italics not in the original.

[7] *The Antarctic Manual for the Use of the Expedition of 1901,* p. 34. *Note,* Cape Adare hugs the coast on the margin of anticyclone and migrating cyclones to the northward.

[8] R. DeC. Ward, *Climate,* Putnams, New York, 1908, pp. 165–166.

winds at the winter stations. Of the three expeditions which established stations upon the ice platforms *near* the Antarctic Continent, no one was really located upon the main land area of the Antarctic. One of them, the Swedish expedition under Nordenskjöld, found a complete dominance throughout the year of southwesterly winds (Fig. 7).[9] Another, the British expedi-

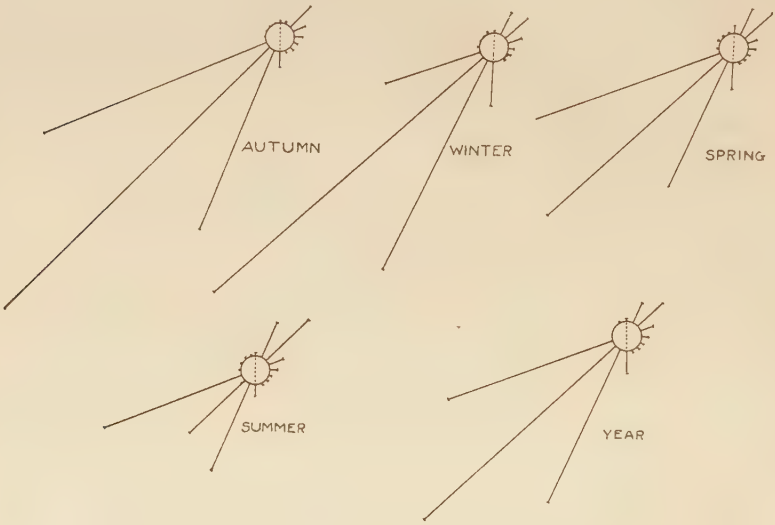

FIG. 7. Wind-roses, Snow Hill Island, West Antarctica (after Bodman)

tion under Scott, found that while the lighter and the moderate winds came from the southeast, the dominating very strong winds (blizzards) swept down from the southwest. The station lay in a sluiceway entering from the southeast, through which passage except during storms the air poured off the Ross Barrier onto the sea.[10] See also p. 174 and Figure 53.

[9] O. Nordenskjöld, "Svenska Sydpolar Expeditionen 1901–03," *Wissenschaftlicher Ergebnisse,* Gösta Bodman, Bd. 2, *Meteorologie.*

[10] Robt. F. Scott, "Results of the National Antarctic Expedition," *Geogr. Journ.,* vol. 25, 1905, p. 367; C. W. Royes, "On the Meteorology of the Part of the Antarctic Regions where the 'Discovery' Wintered,"

The German expedition, which of all has supplied perhaps the smallest amount of essential meteorological data concerning the Antarctic Continent, established its winter quarters upon the *Gauss* held firmly in the sea-ice far off the coast. It is necessary to stress the point that no such general dominance of easterly and southeasterly winds throughout the Antarctic as has been so generally assumed is warranted by the facts. As will be shown, the direction of wind at any place upon the Antarctic Continent is determined by quite other conditions than those which are generally assumed, and it should further be stressed that observed directions of wind made in positions on nearly all sides of the South Magnetic pole have little significance if expressed in terms of the cardinal directions.

THE FIRST SLEDGE JOURNEYS OVER THE ANTARCTIC INLAND-ICE

First direct observation of Antarctic continental conditions.— Of the five great Antarctic expeditions of 1901–4 one only, the British expedition under Captain Scott, supplied any considerable amount of direct knowledge concerning the inland-ice, then as now believed to cover the greater part of the Antarctic Continent. The German expedition under Von Drygalski invaded this inland-ice in Kaiser Wilhelm Land for the distance of a few miles only, and Dr. J. Gunnar Anderson of the Swedish expedition crossed the narrow tongue of the inland-ice over the peninsula of West Antarctica.[11]

The two important sledge-journeys of the Scott expedition over the inland-ice were carried out by Lieutenant Armitage and Captain Scott respectively, and these gave us what was *absolutely our first direct observational knowledge concerning the*

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ibid., p. 389; *National Antarctic Expedition 1901–1904, Meteorology*, Part I, Observations at winter quarters and on sledge journeys with discussions by various authors, 1908; Table on page 507.

[11] H. G. Andersson, *Pet. Mit.*, vol. 50, 1904, p. 30.

air circulation over the Antarctic Continent itself. On *its edge* Bernacchi made most valuable observations three years earlier, clearly indicating anticyclonic conditions for the Antarctic region.[12]

Armitage, 1902. — The sledge journey of Lieutenant Armitage, the first of importance ever to be made over inland-ice in the Antarctic, took its course up the Ferrar glacier outlet to the inland-ice which lies to the westward of the winter quarters of the expedition on McMurdo Sound. Armitage then pushed on in the same general direction to an elevation as determined by aneroid of 8985 feet[13] (corrected official height 7700 feet). Almost from the very beginning of the ascent from the level of the sea, winds were encountered which blew down the slope. Strong blizzards blowing from the same direction were encountered at an elevation taken as 7500 feet while the party was still upon the glacier outlet. At the head of this outlet (uncorrected altitude 8200 feet), "scud was being driven rapidly from the southwest, and from the appearance of the sastrugi[14] that was the prevalent direction of the wind in this locality" (p. 181). "These drifts of hard snow, . . . being always formed by the prevalent direction of the wind, so that even in thick weather, if there are lines of sastrugi, one is to a great extent independent of the compass" (p. 181).

At the extreme point reached by Armitage, which was at an uncorrected altitude of 8985 feet, extending toward the interior of the snow surface, there was apparently a perfectly level plain, but sights taken in different directions with the theodolite showed that the horizon was very slightly elevated in the direction be-

[12] L. Bernacchi, *To the South Polar Regions,* London, 1901, Pt. II, pp. 287–312.

[13] In the absence of levelled profiles all altitudes over inland-ice are unreliable.

[14] Elongated snow-drifts shaped by the winds and with long axis parallel to wind direction.

tween south and east, whereas in the opposite direction it was very slightly depressed.[15]

Scott, 1903. — Captain Scott's sledge journey over inland-ice until the head of the Ferrar Outlet had been reached followed much the same route as that of Lieutenant Armitage and encountered also down-slope winds, but from that point it took a direction slightly more to the northward, so that its general direction was westerly. Scott penetrated the unknown region over the inland-ice for a distance of about two hundred miles and reached an altitude according to his determinations of over 7715 feet.[16] During his entire journey the winds blew from the southwest and hence roughly in the down-slope direction, and the sastrugi showed that this was the prevalent direction when in the winter season fierce blizzards blow from the same general quarter.[17] It appears to the writer, on reviewing the narratives of Armitage and Scott, that an elevation of the inland-ice surface must lie to the southward of Scott's route and that the altitude figures of Armitage have been too greatly modified in the official report.

From these observations by Armitage and Scott it was learned that, whatever might be the local wind direction at the winter quarters of the expedition, here upon the inland-ice the prevalent direction, instead of being east or southeast, is west-southwest down an easterly slope. It must be credited to the shade

[15] Albert B. Armitage, *Two Years in the Antarctic, being a Narrative of the British National Antarctic Expedition,* Arnold, London, 1905, Chapters IX–X.

[16] Note that Armitage's altitude measured as 8985 feet has been officially reduced to 7700 feet or 15 feet less than that of Scott, the commander of the expedition.

[17] These down-slope winds from the southwest as observed by both Armitage and Scott are the ones which, quite oblivious of their true origin, Meinardus and Hann have seized upon to prove that at this level the party had already ascended through the anticyclone into a superimposed cyclone. The fact is ignored that *these winds were encountered from the bottom of the slope near sea-level* (see p. 58).

of Ferrel and to the strong influence of Hann (see p. 121) that neither at the time, nor later, the true significance of these anticyclonic winds was grasped by the expedition. The director of the Meteorological Office, Sir Napier Shaw, who prepared the introduction to the final report of the expedition on meteorology, quite ignored the obvious relationship of wind to snow slope and wrote in the terms of Hann:

> . . . The Antarctic anticyclone, if it exists, is a comparatively superficial effect attributable to the surface cold. But to give an easterly wind there must be sufficient thickness of cold air to reverse the gradient of the upper air, which, as shown by the smoke of Erebus, by cloud observations, and by the observations at high levels, is poleward; 5000 feet is probably an ample allowance for the thickness of the cold surface cap which has an east to west rotation. In order to give a resultant gradient for easterly winds, the gradient of the cold surface layer must exceed that of the westward moving air up above. One requires, therefore, a rapid *change of pressure* in the surface layer, and with that we should expect to find a *rapid temperature gradient poleward*.[18]

Attention should be called to the observations themselves, which showed that the anticyclonic condition extended to the highest point reached, that the poleward movements in the upper air layers are but part of the same anticyclonic vortex, and that there were at the time no real data for a study of the "temperature gradients poleward," *since Scott's sledge-journey toward the pole at the time was made over the Ross Barrier throughout,* which barrier has its upper surface close to the level of the sea and is apparently floating upon it — it was not over the Antarctic Continent, as Scott himself so clearly demonstrated.

Shackleton, 1909. — Two additional studies of meteorological conditions *above the Antarctic Continent* were supplied by the Shackleton British expedition of 1908–9; one of these made by Shackleton himself on his polar sledge-journey, the other by

[18] *National Antarctic Expedition 1901–1904, Meteorology,* Part I, 1908, p. xiii (italics in the original).

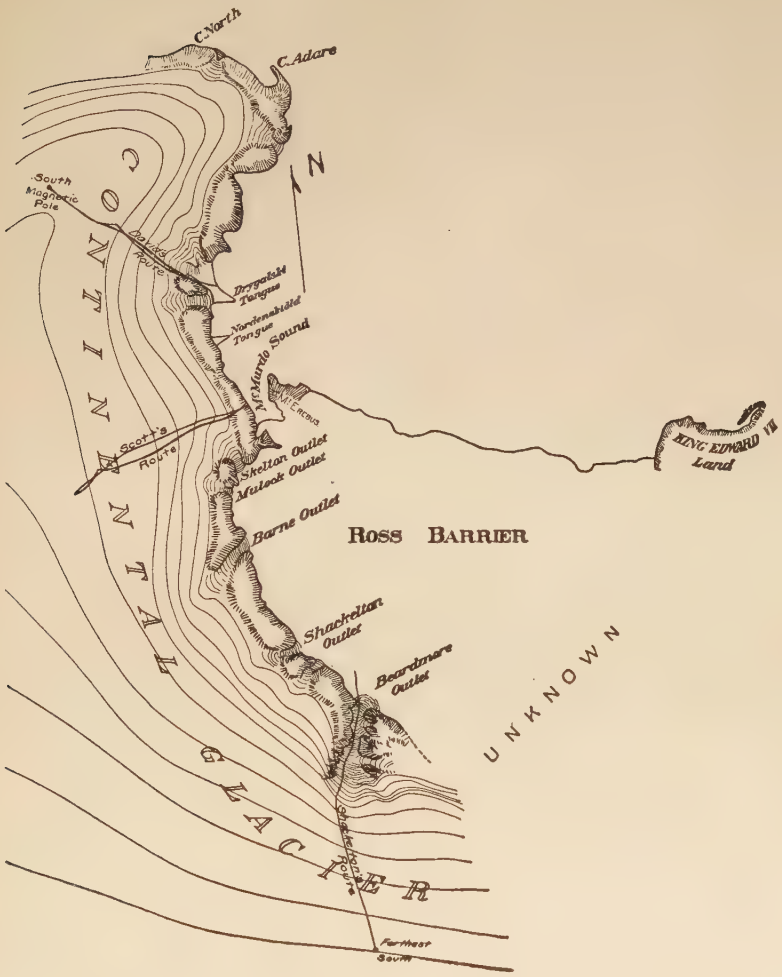


FIG. 8. Generalized map of the surface of the inland-ice of South Victoria Land based on the sledge-journeys of Armitage, Scott, Shackleton and David (from Hobbs, *Earth Features and Their Meaning,* 1912)

Professor, now Sir, T. W. Edgeworth David, F.R.S., on his sledge-journey to the South Magnetic Pole.[19]

Shackleton's route was up the slope from the foot of the Beardmore Outlet in an almost straight southerly direction to an altitude of 10,000 feet or more, yet the winds throughout were head-winds, neither from the east nor the west, but from near the south, which was here the up-slope direction, and this continued to the ultimate position attained, a point distant only 110 miles from the South Pole, *where a terrific blizzard blew for three days almost directly down-slope.* The sastrugi, moreover, indicated clearly that this was the prevailing wind direction (see Fig. 8).

David, 1909. — David, on the other hand, traveled in a quite different direction, about northwest, to and beyond a divide of the inland-ice and then down-slope upon the other side until he reached the Magnetic Pole. For the greater part of this route, then, he was proceeding up-slope. He encountered head-winds until the divide was reached at an altitude of over 7350 feet, after which while he was descending upon the northwest side the winds came from the rear. Upon the return journey these conditions were exactly reversed, thus showing a control throughout by the snow-slope of the inland-ice. The sastrugi, moreover, showed these to be the prevailing wind directions during the winter season (Fig. 9).

In his preliminary report on meteorology in *The Heart of the Antarctic* the wind circulation is discussed by David in the main in terms of the relation to the geographic pole rather than to the ice topography.[20]

The presence of Mount Erebus, an active volcano 13,300 feet

[19] Sir Ernest H. Shackleton, *The Heart of the Antarctic*, two vols., Heinemann, London, 1909, Appendix V of vol. 2. *Meteorology,* by Professor T. W. Edgeworth David and Lieutenant Adams.

[20] *The Heart of the Antarctic,* vol. 2, Appendix V (Professor David and Lieutenant Adams).

FIG. 9. Sketch-map to show the relation of wind-direction to snow-slope of the inland-ice about the Magnetic Pole Plateau of South Victoria Land, based on David's narrative (from Hobbs, *Zeitschrift für Gletscherkunde,* 1910)

high continually emitting vapors within view of the base, was of the greatest value in gaining knowledge of the meteorological conditions of the region about the British winter quarters. At a height of 11,500 to 12,000 feet and within the rim of an outer crater of this volcano, the sastrugi, instead of pointing southeast as they do rather generally on the barrier near the winter quarters, were found to point west-southwest, the direction which they have upon the high plateau of inland-ice to the west of the station. The experience of the southern sledging party, moreover, *while they were still upon the barrier,* was that though

south-southeast was the prevailing direction of wind as indicated by the sastrugi, these locally (*below the outlets from inland-ice*) swung round so as to point between south-southwest and west-southwest.[21] (See Fig. 21, p. 57.)

From the motions observed in the vapor column over Mount Erebus, movements of the air were followed in some instances up to a height of about 20,000 feet. In general these movements conformed to the direction of motion of the higher clouds, and were opposed in direction to the surface air currents. David and Adams speak of these upper currents as indicating air in motion *toward the pole* to replace the air which moves outward from it.

[21] David and Adams, *op cit.*

CHAPTER V

THE EARLY EXPLORATION OF THE GREENLAND CONTINENT

EARLY SLEDGE JOURNEYS OVER THE INLAND-ICE

The air circulation over Greenland in its relation to the Antarctic. — If we now turn from the Antarctic region toward the Arctic, we find wholly different conditions, namely, a frozen sea occupies the region about the North Pole in place of the high continent about the opposite pole. The parallel with the Antarctic region is supplied by the continent of Greenland in a highly eccentric position with its center area removed by some nineteen degrees of latitude from the pole. Because attention has been fixed upon the relation of the earth's general atmospheric circulation to latitude alone, this fact has been quite generally overlooked by meteorologists, though it is vital to a solution of the problem.

In order properly to examine into the observations made by Greenland explorers, it is best to depart for the moment from a strictly chronological order of presentation, so as to take note of a pregnant statement by Peary concerning the winds above the inland-ice. This statement was first published in 1898, after he had made his remarkable sledge-journeys, each of twelve hundred miles or more, across the inland-ice of North Greenland, although he had arrived at the conclusion much earlier. Said Peary:

> Except during atmospheric disturbances of exceptional magnitude, which cause storms to sweep across the country against all ordinary rules, the direction of the wind of the "Great Ice" of Greenland is invariably

radial from the centre outward, normal to the nearest part of the coast-land ribbon. So steady is this wind, and so closely does it adhere to this normal course, that I can liken it only to the flow of a sheet of water descending the slopes from the central interior to the coast. The direction of the nearest land is always easily determinable in this way. The neighbourhood of great fjords is always indicated by a change in the wind's direction; and the crossing of a divide, by an area of calm or variable winds, followed by winds in the opposite direction, independent of any indications of the barometer. (*Geogr. Journ.*, vol. 11, 1898, pp. 233–234.)

This statement by Peary was the starting point of the writer's inquiries into the nature of the air circulation above continental glaciers, and in treating of the earlier, as well as of the later, explorations the test will be applied throughout.

FIG. 10. Map and section showing the profile of the inland-ice of south Greenland and the winds encountered by Jensen in the months of July and August, 1878 (based on Jensen's map and on his tables of observations)

Jensen, 1878. — If we neglect the rather abortive attempts of Dalager in 1751 and of Baron Nordenskiöld in 1870 to penetrate the Greenland Continent, the first successful attempt is that of the Danish explorer, Lieutenant J. A. D. Jensen, who in 1878 pushed his way up over the inland-ice from Fredrikshaab on the southwest coast to a distance of about 70 kilometers,

reaching an elevation according to his figures of about 1320 meters.[1] His map indicates a confirmation of Peary's broad generalization, so soon as the wind directions are entered upon it. (See Fig. 10.)

A. E. Nordenskiöld, 1883. — Baron Adolf Erik Nordenskiöld returned to Greenland in 1883, and this time he succeeded in pushing eastward over the inland-ice from near Disco Bay near the latitude of 68°. He himself reached an altitude upon the inland-ice, according to his figures, of over 1500 meters. From

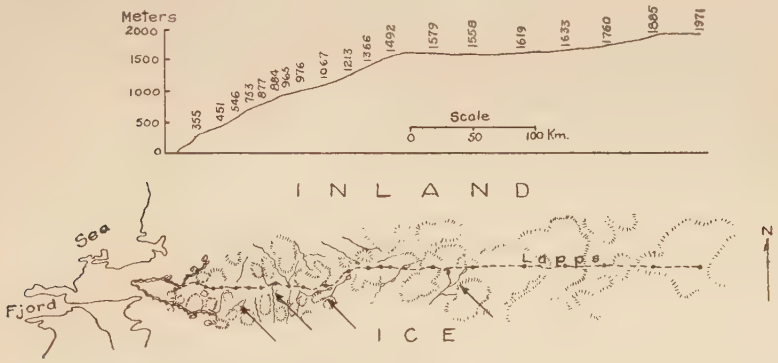


Fig. 11. Map and section to bring out the profile of the snow-ice surface along the route of Nordenskiöld and his Lapps in July, 1883. Upon the maps have been entered the data concerning wind direction extracted from his narrative (based on A. E. Nordenskiöld)

this point his Lapps upon skis went considerably farther, and according to their own statements to an altitude of 1971 meters; the farthest point reached by them being, according to Nordenskiöld's estimate, about 100 kilometers from the coast (see Fig. 11).[2] Here again we find conformity with Peary's dictum concerning the winds.

[1] J. A. D. Jensen, "Expeditionen til Syd-Grönland i 1878," *Med. om Grönland, Kjöbenhavn,* vol. 1, 1879, pp. 1–139; "Astronomiske og Meteorologiska Observationer," *ibid.,* pp. 153–186, 3 maps and many plates.

[2] A. E. Nordenskiöld, "Nordenskiöld's Greenland Expedition," *Nature,* vol. 29, 1883–1884, pp. 10–14, 39–42, 79–81.

Peary, 1886. — Robert E. Peary, at the time a civil engineer in the United States Navy, started out in 1886 on his long series of explorations in Greenland by an attack upon the inland-ice from the west coast at a point near the parallel of 69°. In a succession of fierce gales which faced him almost throughout and continued to the farthest point reached, he pushed his way an estimated 100 miles inward from the ice margin, where he attained an altitude determined by aneroid readings to be 7525 feet. The very rough section of Figure 12 has been based upon his aneroid readings at his camps with such estimates of march distances as he gives in his narrative.[3]

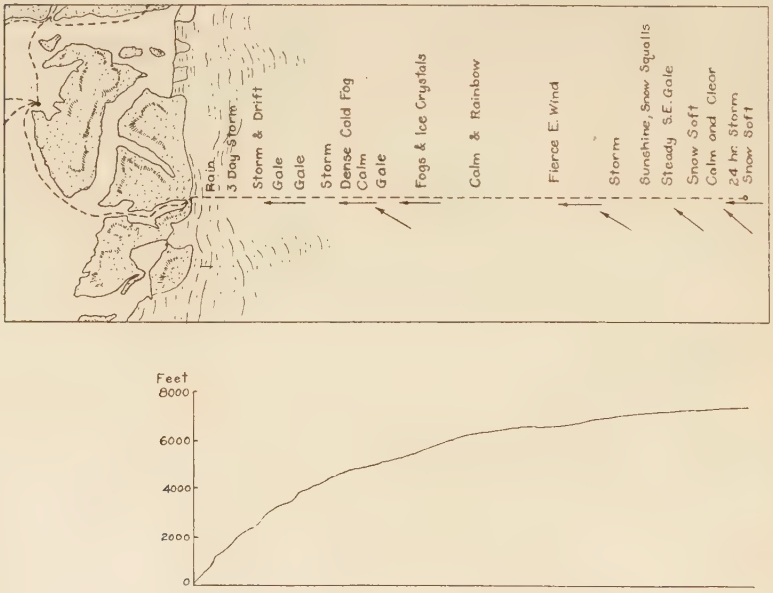


FIG. 12. Route and rough profile of Peary's sledge-journey over the inland-ice in June and July, 1886, with his wind directions entered upon the map (based on Peary)

[3] R. E. Peary, "A Reconnaissance of the Greenland Inland Ice," *Journ. Am. Geogr. Soc.*, vol. 19, 1887, pp. 261–289. Also *Northward over the Great Ice*, 1898, vol. 1, pp. 1–40.

Nansen, 1888. — The first crossing of Greenland was achieved by Fridtjof Nansen, then known chiefly as a champion *ski lubber* of Norway. Ascending the ice from the east coast during the months of August and September, he kept in the main to a nearly westerly course near the parallel of 64° (see Fig. 13).

Fig. 13. Sketch map of Greenland showing the sledge routes of explorers previous to 1910

He found the snow-ice mass to have a domed surface with the faintly indicated divide considerably nearer the east than the west coast (see Fig. 14).[4] The meteorological data were subse-

[4] F. Nansen, *The First Crossing of Greenland*, 2 vols., London, 1890.

quently worked up by Mohn,[5] the distinguished Norwegian meteorologist, who after averaging the wind directions in percentages for each of the principal directions for the eastern and western slopes of the inland-ice, concluded:

> We see here a sharply marked difference between the two sides of Greenland. On the east side the northwest winds were the most frequent, while the easterly ones were somewhat rare. On the west side, on the other hand, the easterly winds were the most frequent, while the westerly ones were very rare. The northerly and the southerly winds were on both sides not very frequent, though the south winds reached 11 per cent on the west side, while on the east side they were only half as frequent.
>
> The prevailing winds were therefore land winds which blew from the interior toward the coasts. This points to a maximum air pressure in the interior and to air currents toward it which flow off on both sides over the slope toward the sea.

Nansen himself in his narrative account, which was published two years earlier, said that — "the winds which prevail on the coasts have an especial tendency to blow outwards at all points."[6] Mohn and Nansen did not plot the wind directions upon the route chart, but this has here been done from the data in the Mohn-Nansen report. The larger arrows indicate winds which were of sufficient strength to be especially noted in Nansen's narrative.

Peary, 1892–95. — In 1892 with a single companion, Eivind Astrup, Peary undertook that remarkable sledge-journey which totalled 1300 miles across the inland-ice of north Greenland (see Fig. 13, p. 43). On his return he found the ship waiting to take him back to civilization, and as he then immediately set about the preparations for another expedition, no time was found to write up his results. His diaries describing the sledge-journey were in consequence given over to Dr. Cyrus C. Adams,

[5] H. Mohn and F. Nansen, "Wissenschaftliche Ergebnisse von Dr. F. Nansen's Durchquerung von Grönland 1888," *Pet. Mit.*, Ergängsungsh. No. 105, 1892, p. 46.

[6] *Op. cit.*, vol. 2, p. 496.

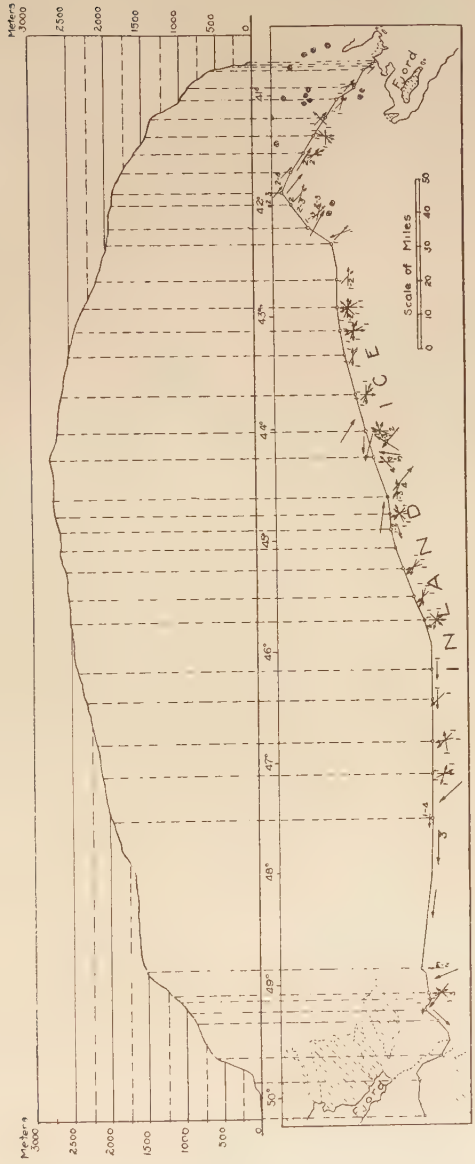


FIG. 14. Section across the inland-ice near the parallel of 64°, together with a map upon which the wind directions have been entered from Mohn and Nansen's tables (after Mohn and Nansen)

who prepared an account which was published by the Royal Geographical Society.[7] The law which, when he was himself able to publish his scientific results, Peary stated so tersely (see p. 39), is found no less clearly stated in the summary of his diary by Adams:

> The wind blew strongly and incessantly, and its almost invariable direction was down the slopes of the ice-cap. When they were west of the great divide, or backbone of the inner ice mass, the wind swept down the gentle slope from the east, and *vice versa* when they were east of the divide. The wind was more variable in direction, and not so strong at the summit of the divide, though strong enough rapidly to drift the fog that constantly enveloped them.[8]

It is much to be regretted that we have not the data concerning locations to construct from Peary's diary a satisfactory profile of this most interesting transection of Greenland throughout (see Fig. 15), but a wealth of notes concerning the elevations and the wind directions as well is to be found in Astrup's excellent narrative;[9] all of which confirm in the most satisfactory manner the generalization of Peary above stated.

In 1895 Peary again made the transection of northern Greenland, this time along a near but somewhat different route; and it was at the conclusion that he so succinctly expressed the relationship of wind direction to snow-slope over inland-ice which has been quoted near the beginning of this chapter.[10]

Garde, 1893. — In June of 1893 Lieutenant, now Admiral, T. V. Garde of the Danish Navy undertook an important exploration of the inland-ice in southwest Greenland, and pene-

[7] C. C. Adams, "Lieut. Peary's Arctic Work," *Geogr. Journ.*, vol. 2, 1893, pp. 303–316. See also Peary's *Northward over the Great Ice*, 1898, vol. 1, Chapters X–XIII.

[8] Adams, *op. cit.*, p. 308.

[9] Eivind Astrup, *With Peary near the Pole*, Pearson, London, 1898, pp. 362, illustrated.

[10] R. E. Peary, "Journeys in North Greenland," *Geogr. Journ.*, vol. 11, 1898, pp. 233–234; *Northward over the "Great Ice,"* 1898, vol. 2, Chapters XIII–XVI.

trated about 100 kilometers from the margin, returning on a quite different route.[11] He supplied valuable meteorological data, so that from his tables we have plotted the wind directions upon his map and also prepared a profile (Fig. 16). Though the quite irregular boundaries of the inland-ice, the frequent *nunataks,* and the narrowness of the ice-dome within

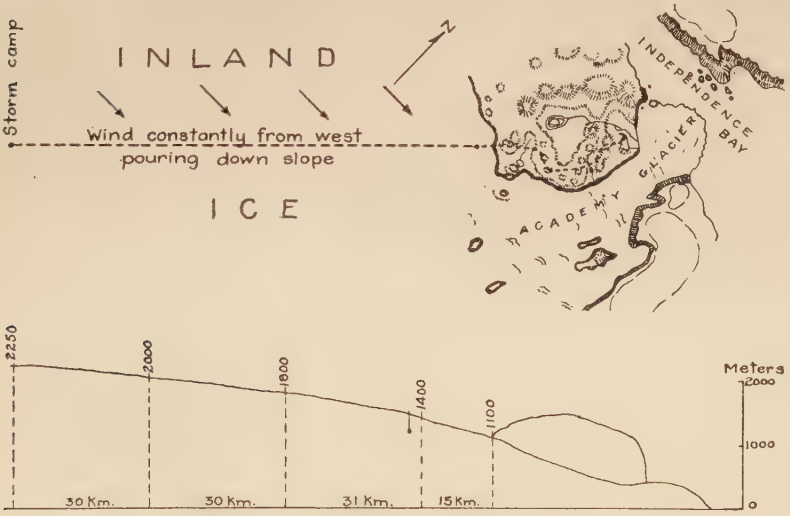


Fig. 15. Wind directions on Peary's route in northeast Greenland (based on Peary)

this district, all introduce certain irregularities, yet the general control of the wind direction by the snow-slope is apparent.

Erichsen, Trolle and J. P. Koch, 1906–8. — This Danish Northeast Greenland Expedition of 1906–8, notwithstanding the loss of its intrepid leader, Mylius Erichsen, together with his companions while upon the fateful sledge-journey over the inland-ice along the coast of the northeast foreland, spent two winters in the vicinity of Danmarks-Havn near the 76th parallel

[11] T. V. Garde, "Beskrivelse af Expeditionen til Julianehaab District 1893," *Med. om Grönl.,* vol. 16, 1896, pp. 71, maps and plates.

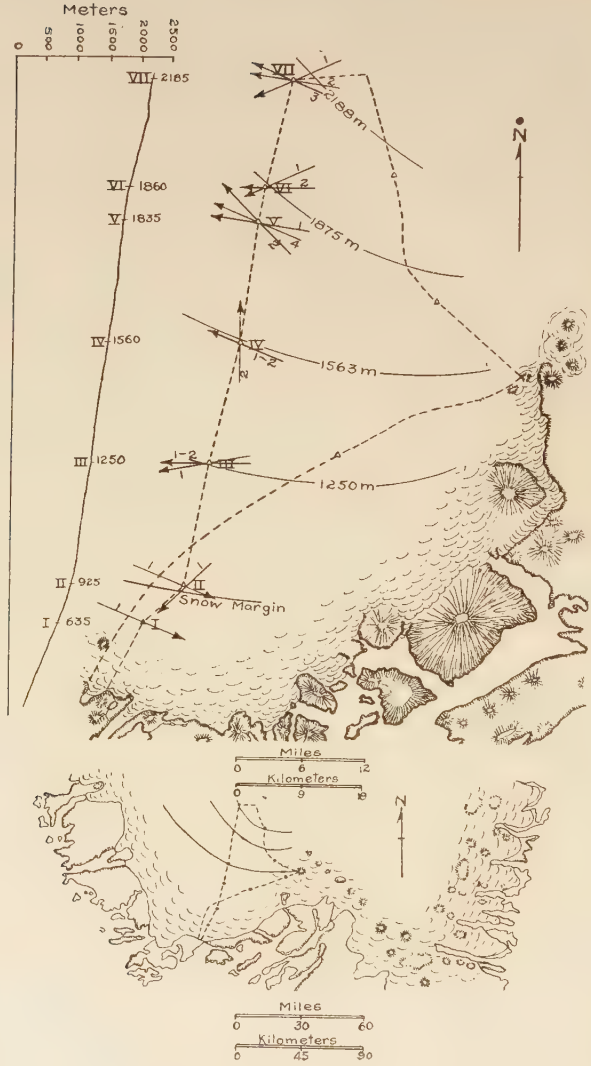


FIG. 16. Map and profile of the borderland of the inland-ice of Greenland in the Julianehaab district with wind directions in June, 1893 (after and based upon Garde)

of latitude, and the preliminary report, published in 1909,[12] by Trolle, who had succeeded Erichsen in command, showed that all strong winds of this east coast come from the northwest, the down-slope direction upon the inland-ice, with deviation from earth rotation. Says Trolle:

> In the middle of February the sun came back, and May and June formed a period of fogs and light sea-breezes. Otherwise, the wind was constantly from the north-west, this being the result of the high pressure of air which is found over the inland ice (p. 68).

De Quervain and Stolberg, 1909. — Two well-known Swiss meteorologists, Dr. Alfred de Quervain and Dr. A. Stolberg, made an attack upon the inland-ice of Greenland starting out in July, 1909, from the west coast in latitude 71° at a point somewhat north of Peary's first line of attack, and they advanced a distance of about 100 kilometers, where the altitude was given as about 1700 meters. From the map of their route and from the data supplied in their narrative, it is possible to construct a profile, and upon their map to plot the wind directions. Again we find strong control by the snow-slopes of the inland-ice (Fig. 17).[13]

THE THEORY OF THE GLACIAL ANTICYCLONE PROMULGATED IN 1910–11

First statements of the theory. — In articles first published in the *Proceedings of the American Philosophical Society* and in the *Zeitschrift für Gletscherkunde,* and after revision published a year later in *Characteristics of Existing Glaciers,*[14] the

[12] Lieutenant A. Trolle, R.V.M., "The Danish North-east Greenland Expedition" (with map and illustrations), *Scot. Geogr. Mag.,* vol. 25, 1909, pp. 57–70.

[13] Dr. A. de Quervain and Dr. A. Stolberg, *Durch Grönlands Eiswüste, Reise der Deutsch-Schweizerischen Grönlandexpedition 1909 auf das Inlandseis,* Singer, Strassburg u. Leipzig, 2te Aufl., 1911, pp. 180, map and illustrations.

[14] See footnote on page 1.

writer first promulgated the theory of the glacial anticyclone for the two ice-covered continents of Greenland and the Antarctic, the only ones which exist today. This atmospheric circulation is not determined by latitude in terms of the Ferrel conception for the higher latitudes, but, on the contrary, was assumed to

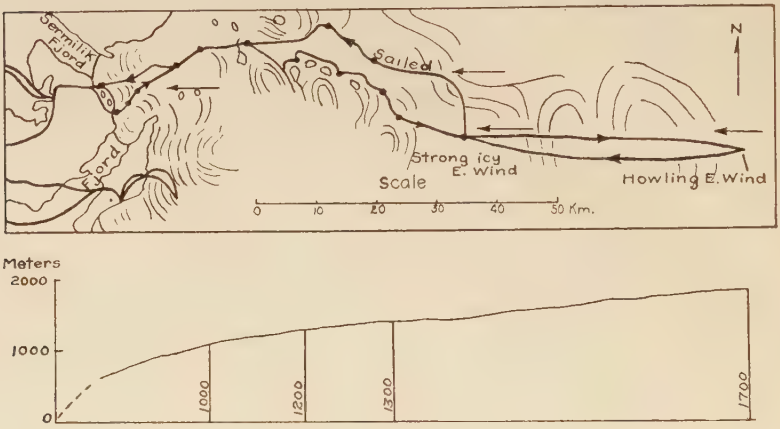


FIG. 17. Map and profile of the sledge-route of De Quervain and Stolberg over the Greenland inland-ice with wind directions in July, 1909, added (after and based on De Quervain and Stolberg)

result directly from conditions of radiation at the domed surface of the inland-ice (Figs. 1, 2 and 18).

Essentials of the Theory. — As already stated, the generalization by Peary concerning the surface air circulation over the continent of Greenland, was the starting point of the writer's studies, and the narratives as well as the scientific reports by various exploring parties made over one or the other of the two continental glaciers were carefully examined for the data. Inasmuch as the sequel will deal with the evidence supporting each element in the framework of this theory, it will suffice merely to mention here what these elements are.

Absolutely essential to the strong strophic centrifugal circula-

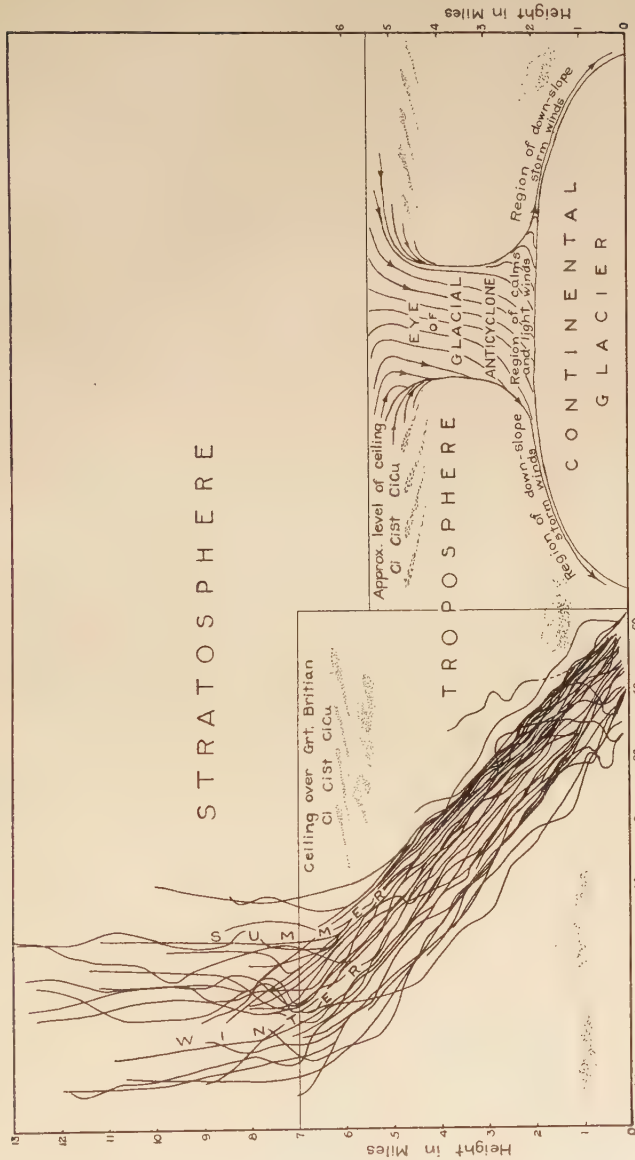


FIG. 18. Diagram to show the character of the glacial anticyclone. At the left data obtained by sounding balloons (after Sir Napier Shaw)

tion of the surface air above the inland-ice is its dome-shaped surface. Were these great glaciers fashioned with their upper surface a horizontal plane or some form of basin-like depression, no such strong circulation would be possible.

Likewise essential to the generation of the fixed anticyclonic circulation is the abstraction of heat from the layer of air immediately superjacent to the snow surface. This layer of air rendered more dense through abstraction of heat, slides outward on the sloping surface under the influence of gravity so as to displace warmer, and therefore lighter, air at lower levels toward the margins of the dome. The tendency of outward-moving currents to produce a void over the boss of the ice-dome, develops a downdraft of air of anticyclonic nature above the central area. Moisture which is locked up in the ice-particles of the cirri and other high-level clouds is by the adiabatic elevation of temperature in the slowly settling air over the interior transformed completely, first into water, and later vaporized before the surface of the ice is reached. The sensible heat thereby transformed into latent heat, tends to hold back and develop more gradually the anticyclonic circulation. Once well started, however, the centrifugally directed surface winds develop at the accelerated rate which is characteristic of all velocities that are due to the action of gravity. When blizzard velocity has been attained, the descending winds at the edge of the ice-cap are damped because adiabatic elevation of temperature overcomes the lowering of temperature brought about through contact with the snow-ice surface. As this stupendous thermodynamic air-engine here comes to a halt and completes a stroph, some snow is precipitated near the margins, apparently during a slight reversal to cyclonic conditions during a very brief period, and latent heat is liberated to increase the elevation of air temperature which occurs at each termination of a blizzard. The bulk of the precipitation for the nourishment of the glacier is, how-

ever, due to the separation from surface layers of air within the interior region.

The characteristic weather, then, over continental glaciers is an alternation of blizzard and calm. The nourishment of the

Fig. 19. Maps to show positions of glacial anticyclones:
A. Existing continental glaciers and overlying anticyclones
B. Pleistocene continental glaciers and anticyclones
(Hobbs, 1911)

glacier, instead of being due to the forcing of low-lying clouds to higher levels, as is true of mountain glaciers, is here brought

about mainly through the pulling down of high-level clouds to the glacier surface. The snow deposited, so far as it is not merely lifted and carried by the blizzard, is laid down largely within the interior region, and this snow may at times be in part swept up by some succeeding blizzard and carried outward to be deposited about the margins of the dome. From the higher slopes it is clear that it is so removed. The surface of the glacier thus appears to be, in fact, fashioned by a centrifugal snow broom, and, except in the marginal zones, not by internal movements of the ice mass itself. Upon the margins of the dome the downslope winds, always with clockwise deviation because of earth rotation, have the character of the well-known foehn.

Great as is the importance of the glacial anticyclones of the present, those connected with the great continental glaciers of the Pleistocene must have been vastly more extended and exercised an even greater influence upon the earth's general circulation (see Fig. 19).[15]

The climatic zones which are characteristic of the present age would appear to be due largely to the existing glacial anticyclones, and the accentuation of climatic zones during the culmination of glacial periods must have been so much the more marked (see Chapter XI). Through the greater part of geological history, climatic zones appear to have been either lacking entirely or but faintly developed, as the study of distribution of delicate organic forms sensitive to temperature range would demonstrate.

[15] W. H. Hobbs, "The Pleistocene Glaciation of North America Viewed in the Light of our Knowledge of Existing Continental Glaciers," *Bull. Am. Geogr. Soc.*, vol. 43, 1911, pp. 641–659.

CHAPTER VI

THE SECOND PERIOD OF EXPLORATION OF CONTINENTAL GLACIERS

THE IMPORTANCE OF THE EXPEDITIONS FROM 1911 TO 1914

The expeditions in order. — When *Characteristics of Existing Glaciers* was published in 1911 a very remarkable period of exploration of the world's two continental glaciers was about to open. In the southern summer of 1911 to 1912 Captain Amundsen [1] (Norwegian) and Captain Scott [2] (British) penetrated in succession the Antarctic Continent and attained the South Pole; while upon the continent of Greenland epoch-making transections from coast to coast were in 1912–13 carried out in the central region by Professor de Quervain [3] (Swiss) and by Captain J. P. Koch [4] (Danish); each expedition passing through or near the central area of the ice-dome. Other vastly important expeditions were carried out by Rasmussen [5] (Danish) in north Greenland in 1912 and by Filchner [6] (German) in the

[1] Roald Amundsen, *The South Pole*, 2 vols., 1913.

[2] *Scott's Last Expedition*, 2 vols., 1914.

[3] A. de Quervain, *Quer durchs Grönlandseis, Schweizerische Grönland-Expedition 1912–13*, Reinhardt, München, 1914, 196 pages, pls. 15, figs. 36, and map.

[4] J. P. Koch, "Unsere Durchquerung Grönlands 1912–1913," *Zeitsch. d. Ges. f. Erdkunde z. Berlin*, 1914, pp. 34–50; A. Wegener, "Vorläufiger Bericht über die wissenschaftlichen Ergebnisse der Expedition," *ibid.*, pp. 50–54.

[5] Knud Rasmussen, "Report of the First Thule Expedition 1912," *Meddelelser om Grönland*, vol. 51, 1914, pp. 283–340, pls. and map; P. Freuchen, "General Observations as to the Natural Conditions in the Country Traversed by the Expedition," *ibid.*, pp. 341–425.

[6] Dr. Erich Przybyllok, "Deutsche Antarktische Expedition, Bericht über die Tätigkeit nach Verlassen von Südgeorgien," *Zeit. d. Ges. f. Erdkunde z. Berlin*, 1913, pp. 1–17, pls. 2, figs. 3.

same year in the Antarctic. In a widely separated portion of the Antarctic Professor Mawson [7] (Australian) made explorations of great importance in the years 1911–14.

Final reports on earlier expeditions. — Within the period 1911–15 important final reports of earlier expeditions became

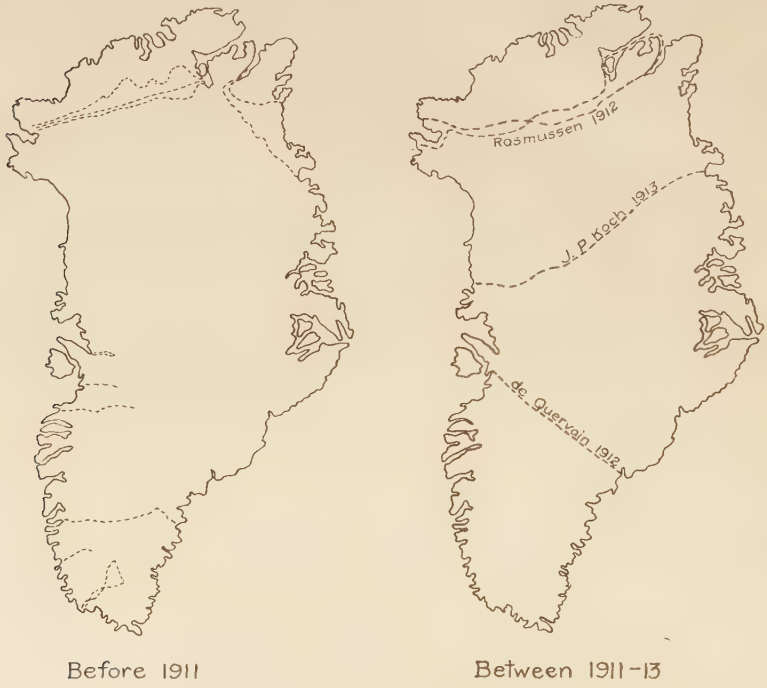


FIG. 20. Maps showing the routes of sledge-journeys across the inland-ice of Greenland. A, before 1911; B, between 1911 and 1915.

available; notably that of David on the geology (and meteorology) for the Shackleton expedition of 1907–9,[8] and the full

[7] Sir Douglas Mawson, *The Home of the Blizzard,* 2 vols., Lippincott, 1914; "Australasian Antarctic Expedition," *Geogr. Journ.,* vol. 44, 1914, pp. 257–286, maps and pls.

[8] T. W. Edgeworth David, *British Antarctic Expedition 1907–1909, Geology,* vol. 1, 1914 (Chapter II, "Meteorological Notes with Special Reference to Temperature, Snowfall and Ablation").

reports of the Danish Northeast Greenland Expedition of 1906–8.[9]

The enlargement of our knowledge of Greenland during the years 1911–15 can be best appreciated by examination of the comparative maps in Figure 20.

Discussion by David in 1914. — In 1915 the writer published a discussion of the bearing of the observations made in connection with the expeditions carried out during the few preceding years, as well as of the late reports of the earlier expeditions, so far as these related to the theory of the glacial anticyclone.[10] In outline it is planned to review these data here, but before doing so it seems best to take up for consideration the valuable report of Professor Sir Edgeworth David on the meteorology of the Shackleton expedition of 1907–9, a report which appeared in 1914

[9] Alfred Wegener, *Med. om Grönl.*, vol. 42, 1911, pp. 125–355; W. Brand and A. Wegener, *ibid.*, 1912, pp. 447–562.

[10] The Rôle of the Glacial Anticyclone in the Air Circulation of the Globe," *Proc. Am. Phil. Soc.*, vol. 54, pp. 185–225, figs. 11.

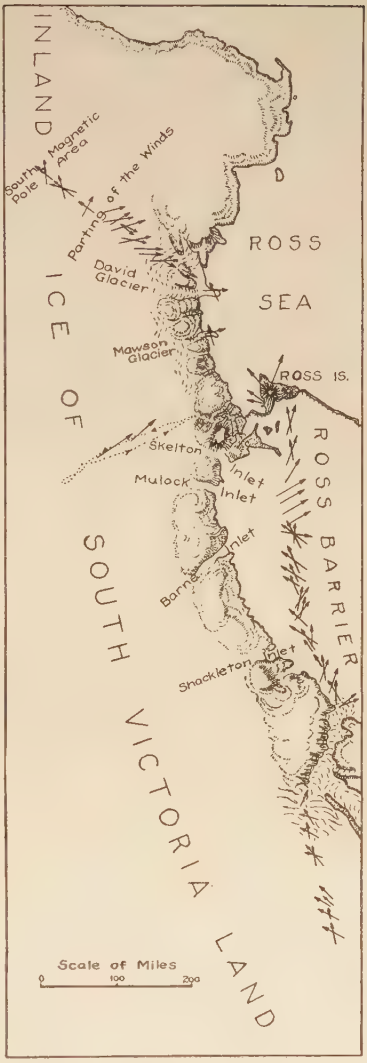


FIG. 21. Sketch-map of South Victoria Land showing the directions of dominating strong winds as indicated by sastrugi (after David)

but did not come to the writer's attention until some years later.

David's monograph contains a very valuable map upon which are represented assembled observations concerning the pointings of sastrugi, and hence of the prevailing strong wind directions over the Antarctic inland-ice and the neighboring shelf-ice for all the expeditions made previous to 1909 (see Fig. 21). Nothing could be more convincing than this map to show

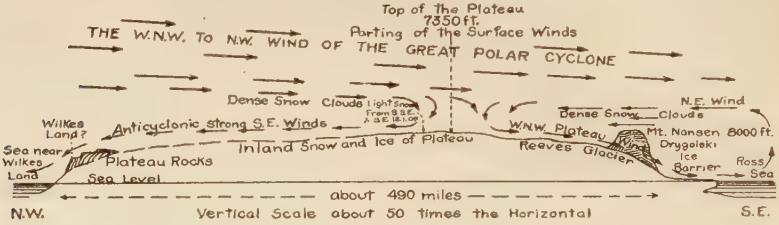


FIG. 22. Section across the Magnetic Pole Plateau of South Victoria Land with overlying air circulation (after David)

that the anticyclonic circulation over the Antarctic region is determined by the topography of the inland-ice and is a direct consequence of its domed surface. David says:

> So far the winds follow the direction which they might be expected to take on the theory of streams of heavy cold air blowing spirally outwards down the slope of the inland-ice from the summit of the main "ice divide."

A generalized section (Fig. 22), however, shows a theoretical cyclone above the anticyclone and Hann (citing Meinardus) is quoted as follows:

> These considerations will also do away with the difficulty of explaining the ice masses radiating away from the Antarctic Continent for the centre of a great fixed anticyclone is not only poor in snowfall, but is rather a place of increased evaporation; it is a region of starvation, not of alimentation of ice and glaciers.
>
> But if cyclonic westerly winds extend into the higher altitudes of the Antarctic Continent, provision is made for the conveyance of vapour and for precipitation. This precipitation will not be wanting even in the interior of Antarctica.

It will be evident to all who have followed the discussion above and especially my summarized statements at the conclusion of my *Characteristics of Existing Glaciers*,[11] that my good friend, Sir Edgeworth David, is in error when he adds: "Professor Hobbs in his *Characteristics of Existing Glaciers* has followed Hann's views." It is the rôle of the ice-particles derived from the high-level clouds as they are brought down to the glacier surface, and adiabatically melted and vaporized as they are drawn down in the anticyclone, which Sir Edgeworth has overlooked, but which I believe to be the source of the snow that nourishes the two continental glaciers of Greenland and the Antarctic.

CONFIRMATORY EVIDENCE FOR CENTRIFUGAL SURFACE-AIR CIRCULATION

De Quervain's sledge-journey across south-central Greenland. — The numerous long sledge-journeys over the inland-ice of Greenland which were carried out between 1911 and 1915 have, as already pointed out, greatly extended our knowledge concerning the air circulation above this vast region. The Swiss expedition under Dr. Alfred de Quervain made the transection of the Greenland Continent from the west coast in latitude 70° N. to the east coast in latitude 66° N. Whereas during the first three weeks, or until the ascent had been made to the interior plain, the outward-blowing down-slope winds had been so constant in direction as to be depended upon in laying the course, shifting winds of light force were encountered toward the interior. Once fairly over the highest part of the ice dome, however, where the slope took on a descent toward the east of only eight minutes of arc, the wind blew from the northwest and continued in that general quarter until the expedition was near the east coast.[12]

[11] See especially the Afterword and pp. 1–5. [12] De Quervain, *l. c.*

J. P. Koch's sledge-journey across north-central Greenland. — Captain, now Colonel, J. P. Koch, already a veteran in Greenland exploration, made his transection of Greenland near but north of its widest portion, ascending the inland-ice upon the east coast in latitude 79° and coming down to the west coast in latitude 71°. On this journey he was accompanied by the well-known meteorologist, Alfred Wegener. His experiences, as brought out in his preliminary account, tallied well with those of De Quervain in the region somewhat farther to the southward. Strong head-winds and heavy storms were faced during the ascent from the east coast, an area of light winds and calms was passed through in the central portion of the journey, and winds from the rear during the descent to the west coast made sailing a great aid.

Rasmussen's sledge-journeys across northern Greenland. — In 1913 Knud Rasmussen made a double crossing of the inland-ice of northern Greenland, starting from the Clements Markham Glacier on the northwest coast and coming down to Denmark Fjord on the northeast coast. On the return the start was made from Independence Fjord and the journey terminated at Thule (North Star Bay) not far to the south of the starting point.[13] The wind directions for the route are plotted upon his map (Fig. 23), and when these are compared with his profile of the route, they display with great clearness the centrifugal air circulation above the inland-ice, developed and controlled throughout by the surface slope of the ice. The divide was found to the east of the center of the profile at an altitude of 2225 meters. On the steeper eastern side of the section the outward-blowing winds were somewhat more constant. After leaving Camp XII on the eastward journey Rasmussen entered in his diary: "We are going downhill now, it seems, and nearing regions that bear more traces of wind. We can see it from the

[13] Rasmussen, *op. cit.*

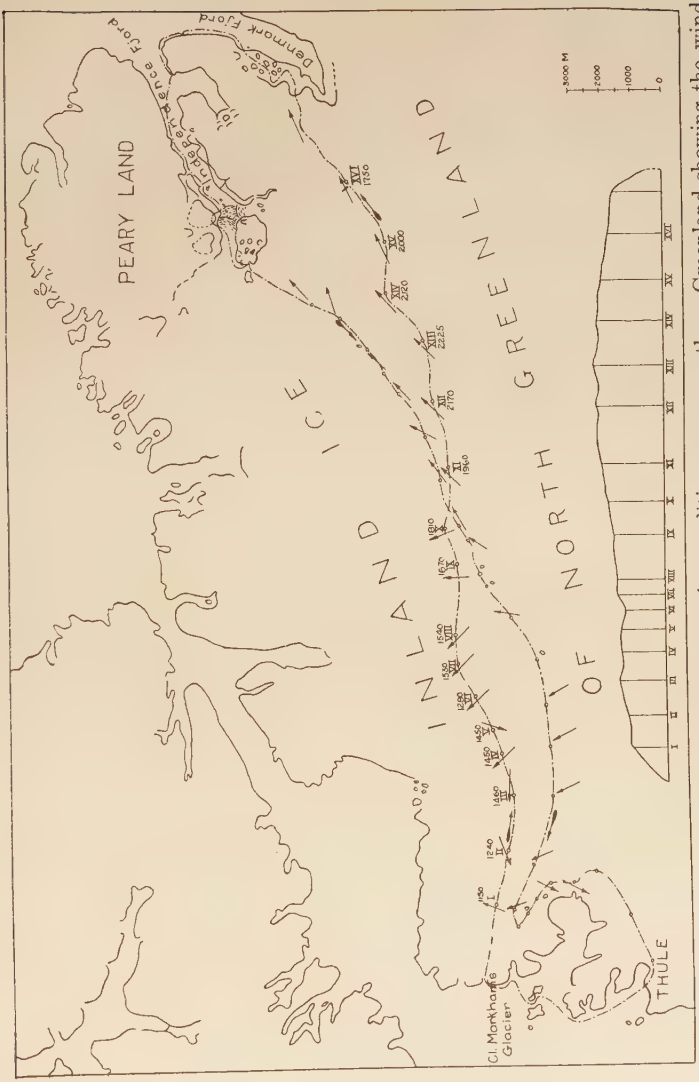


FIG. 23. Track map and profile of Rasmussen's expedition across northern Greenland showing the wind directions (after Rasmussen)

snow, which is wind-furrowed now . . . furnishing a valuable aid to direction" (p. 335).

At Camp XIV in altitude 2120 meters he notes, "It is good firm going now, and we seem to be getting into regions where

THE ANTARCTIC REGIONS AS KNOWN AT THE PRESENT TIME.

FIG. 24. Map of the Antarctic region; *a*, *b*, *c*, *d*, *e* and *f* the penetrations over the inland-ice by Amundsen (*a*), Scott (*b* and *c*), David, and Mawson (*e* and *f*), respectively

the snow does not lie long." At Camp XVIII, he notes, "A gale starting up from southwest (p. 336)." "All down the eastern slope of the inland-ice the snow is smooth and hard.

. . . The ridges and furrows in the snow, here formed by WSW and SW winds seem to indicate a more constant direction of the winds than on the western side" (p. 347). After reaching the "Zigzag Valley" near the end of the section and beneath the great peninsula of Crown Prince Christian Land lying to the

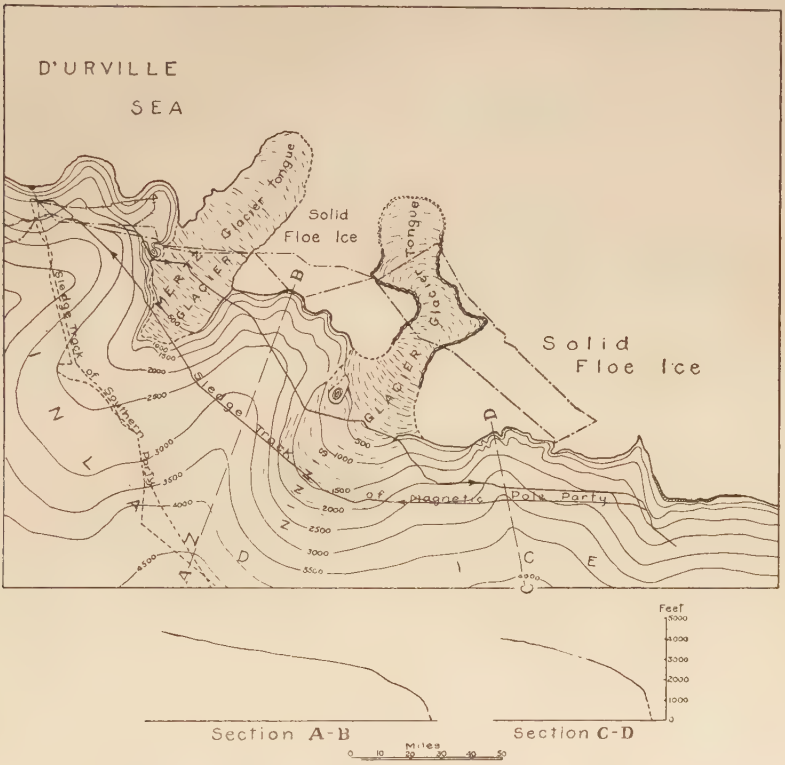


FIG. 25. Map of Adelie Land showing contours of the inland-ice and the routes of sledge-parties (after Mawson)

east and southeast, this last mentioned domed mass takes control of the local winds which in consequence now come from the easterly quarter. Rasmussen says, "It was blowing a stiff easterly gale, the wind rushing down from the ice and tearing

through the valley with such fury as to send the small stones flying about our ears."

Upon the western slope of this section — west of 60° of longitude — the snow was found to be largely blown off the underlying ice by the stiff winds, and it remained in isolated patches only, whereas in the more central area the snow formed a continuous cover.

Mawson's experiences in Adelie Land, Antarctic. — Mawson's Antarctic expedition wintered in two stations separated

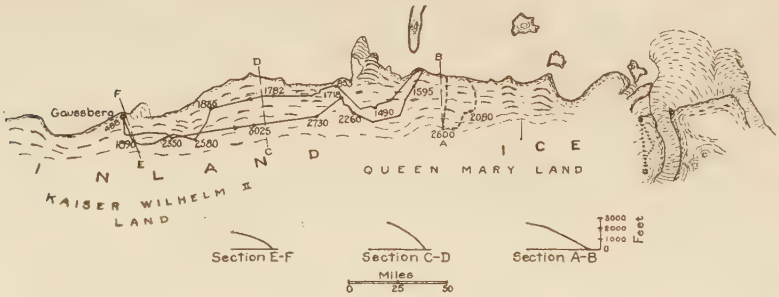


FIG. 26. Map of Queen Mary Land and Kaiser Wilhelm Land (after Mawson)

by some 40° of longitude, Adelie Land and Queen Mary Land (Figs. 25–26), both of them upon the coast which was cruised along by Wilkes and was long known as Wilkes Land. At these stations during summer and winter alike storms blew off the ice onto the sea almost incessantly, so that Mawson has called the region, "The Home of the Blizzard."[14] These storms come from the southeasterly quadrant, as would be true of downslope winds deflected by earth rotation, and their effect is to keep the near-shore portion of the sea clear of pack-ice, though they make it next to impossible for ships to reach the shore save only during those rare intervals when the wind dies down (see p. 7 and Fig. 3). The inland-ice margin is at the shore, and

[14] Mawson, *The Home of the Blizzard*, 2 vols., Lippincott, 1914.

there are ice-tongues and small areas of shelf-ice (see Figs. 25 and 26). The slopes of the inland-ice rise from the shore in the manner already found to characterize it wherever it is unconfined by a rampart of mountains.[15]

In his preliminary report,[16] Mawson has summarized the meteorological conditions of the region as follows:

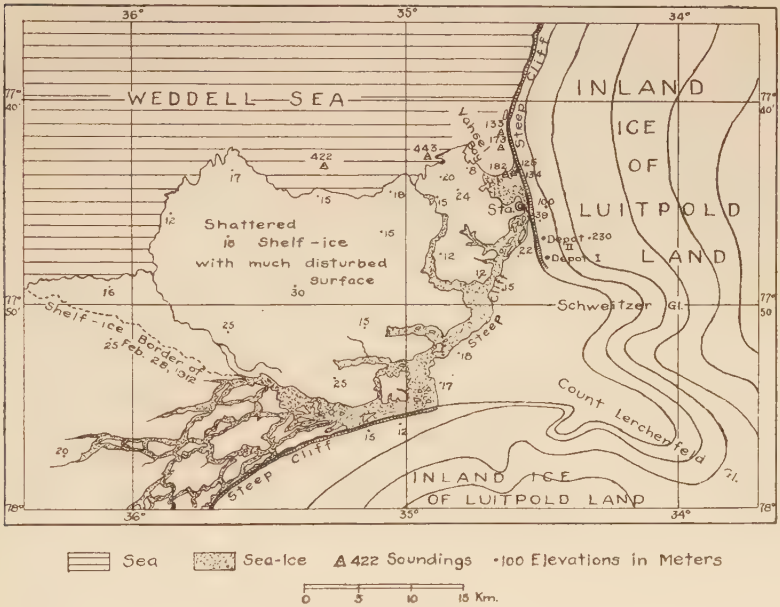


FIG. 27. Map of the inland-ice and shelf-ice of the Luitpold Coast (after Filchner and others)

Although summer was at its height, the weather proved little better than a succession of gales, directed off the land, veering between south and southeast (p. 264).

The absence of pack-ice is due to the persistent gales setting off the land . . . (p. 265).

The average wind velocity in Adelie Land proved to be far beyond anything previously known. The charts of the self-recording instruments

[15] *Characteristics of Existing Glaciers*, Chapter XIV.

[16] D. Mawson, "Australasian Antarctic Expedition 1911–1914," *Geogr. Journ.*, vol. 44, 1914, pp. 257–286, maps and plates.

showed the average for the whole year to be 50 miles per hour. Average hourly velocities of 100 miles and more were common, and twenty-four hour averages of 90 miles were recorded. . . .

. . . even in the height of summer blizzard followed blizzard in rapid succession. . . .

. . . It became apparent that winter quarters was located in the vicinity of a permanent anticyclone (p. 269).

The calm periods are few and far between even in the height of summer (p. 275).

Filchner's observations on and around the Weddell Sea, Antarctic. — The German Antarctic expedition of 1912 under command of Lieutenant Filchner pushed southward in the Weddell

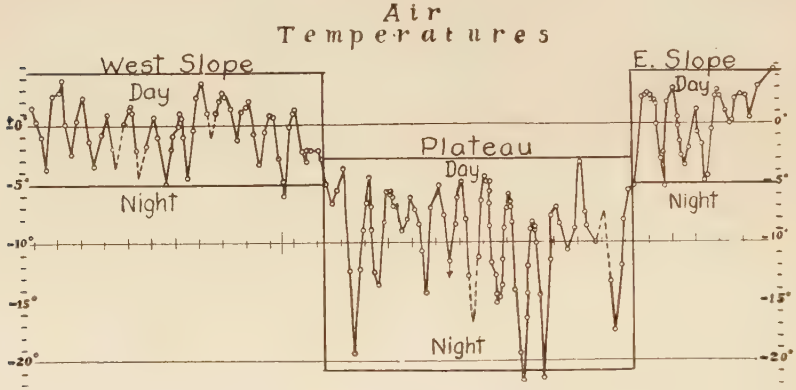


Fig. 28. Daily range of air temperature along De Quervain's profile across Greenland (after De Quervain)

Sea beyond Coat's Coast and discovered the coast of Prince Regent Luitpold Land buried under inland-ice in latitude 76° south (see Fig. 42, p. 124 and Fig. 27). The ship skirted this coast for a distance which extended through two degrees of latitude to a point where broken shelf-ice lay off the land-ice and opposed further progress in that direction.[17] Strong winds blowing off the inland-ice kept the pack-ice off shore, as was

[17] Erich Przybyllok, "Deutsche Antarktische Expedition, Bericht über die Tätigkeit nach Verlassen von Südgeorgien," *Zeit. d. Gesell f. Erdk. z. Berlin,* 1913, No. 1, pp. 1–17, maps.

the case in Adelie Land. A permanent cyclone marginal to the anticyclone above the neighboring continent was indicated for the Weddell Sea. It will be remembered that Sir James Ross in the early forties of the last century had found evidence of cyclonic conditions above the Ross Sea, the other deep indentation of the Antarctic Continent.

CHAPTER VII

THE CHARACTERISTICS OF THE GLACIAL ANTICYCLONE

FOEHN EFFECT OF DOWN-SLOPE WINDS AT INLAND-ICE MARGIN

GREENLAND

Rink. — A valuable reservoir of scientific information about Greenland is to be found in the early work by Dr. Hinrich J. Rink, which appeared in a German translation in 1860,[1] and less complete in an English translation in 1877.[2] Rink's description of the foehn winds as they come down-slope from the plateau to the west Greenland coast is very clear. He says:

> The coming of the warm southeast wind is caused in general by the lowest position which the barometer takes. . . . At the same time the sky shows lightly overcast, especially by long bluish oval clouds of such peculiar appearance that one can scarcely be mistaken if one assumes them to be harbingers of the storm. This cloud cover appears extraordinarily high and never reaches the mountain peaks in the manner of the clouds which are a consequence of the other winds. Meantime the sea and air are now quite calm, and the atmosphere is in summer and winter alike oppressive by reason of the sudden rise of temperature; but the air shows a rare transparency and distant land which at other times one can scarcely see glisten, is made out clear and distinct. Then the storm comes suddenly, but first on the great mountain crests; one sees the snow whirl away over the plateau, and if one is upon the ice of the fjord under the great steep cliffs to the north of Umanak, one hears the storm whistle and roar while it is still quite calm below upon the ice; it blows up there two to three days or even longer, however very irregularly, now falling away gently to a calm, now breaking out again with sudden gusts. At times, but seldom, the arrival of the southeast winds is accompanied by showers

[1] H. Rink. *Grönland, geographisch und statistisch beschrieben, Aus Dänischen Quellschaften,* von A. v. Etzel, Cotta, Stuttgart, 1860, pp. 665.

[2] H. Rink, *Danish Greenland, Its People and Its Products,* London, 1877, pp. 468.

and local rain, especially in January and February; but then there follows bright weather and the wind blows the following days with clear air and with a most striking dryness of the wind. . . .

Without even a drop of running water making its appearance, one sees the snow become thinner and disappear from the land. . . .

When the southeast wind has blown itself out, there follows as a rule wind coming straight from the south and through the Davis Strait, frequently as a storm and bringing with it unsettled weather, or snow and rain. . . . During the south wind the clouds hang low over the fjord and hide all land above the altitude of 1000 feet; the thermometer remains at —10° to —12° in winter and 4° to 5° in summer (pp. 111–112 of German translation).

In a very old book printed in Old Norse and entitled *Konungs Skuggsja,* which means, "The King's Mirror," there is a very remarkable description of the weather conditions on the coast of Greenland and one which harmonizes well with the outrushes of air of the anticyclone, notwithstanding the fact that this account was written about A.D. 1240. It was written by a clergyman and was translated into Modern Norse in Dr. Fridjof Nansen's: "Klimat-forandringer i Nordens historie" (*Videnskaps-akademiets avhandlinger,* vol. I, 1925, No. 3). It has been put into English for publication here by Prof. W. Werenskiold of the University of Oslo. It runs:

When bad weather comes, it comes with greater severity than at most other places, owing to both the force of the wind, and the violence of the frost and snow. But commonly the storm lasts for a short spell only, and it comes with long intervals, when the weather remains fine, although the land is cold; and so is the nature of the *Jokull* (inland ice), that he regularly throws off cold gusts that drive the storm showers away from his face, so that he most often keeps his head bare above him. But as often his neighbors must suffer, because all other lands which lie in the vicinity receive much bad weather from him, as all *that* comes to them, which he throws off himself with cold blasts.

Mohn and Nansen. — Mohn referring to the prevailing "land-winds" which were encountered by Nansen during his crossing of Greenland, states that with the assumed elevation of temperature of 1° C. for each 100 meters descent, a rise of

temperature of 20° is to be expected from the fall of the air from the interior.[3]

Holm. — The meteorological observations carried out by the Holm expedition along the southeast coast of Greenland between 1883 and 1885, have an importance which has been largely overlooked; since for an entire winter season the fall winds from the interior of the continent were found to dominate within the shore region.[4]

The route of the expedition was along the coast, and during the summer this coastal region was more largely under the influence of the low pressure areas which migrated northeastward from Cape Farewell. At Nanortalik, however, throughout two winters the wind blew almost without exception from the northwest, ranging between west-northwest and north-northwest only. At Angmagsalik, which is located within a reëntrant of the coast to the northward of which the continent pushes out to the eastward, the foehn came generally from the northeast or north, though occasionally from the northwest. Jantzen, who treated of the meteorological observations made by the expedition, has connected the foehns closely in time with the passage of cyclones up the coast.[5]

Ryder. — The Danish Greenland expedition of 1891–92, which wintered at Hekla-havn on Scoresby Sound, made a very thorough study of the foehn winds.[6] When these winds blew they came almost invariably from the WNW — the direction of the interior of the continent. In two out of nineteen cases the wind veered to the NW and W. The strength varied from 6 to 9 of the scale. Although, during the days preceding the foehn

[3] *Op. cit.*, p. 46.

[4] G. Holm, "Den Ostgrönlandske Expedition udfort i Aaren 1883–85." *Med. om Grönland,* vol. 9, 1889, pp. 348–408. Résumé in French.

[5] *Op. cit.,* Chapter VI, résumé in French on pp. 348–408. See also Chapter X of this monograph.

[6] *Med. om Grönl.*, vol. 17, 1895, Willaume Jantzen, "Résumé af de Meteorologiska Observationer," pp. 171–180. French résumé on p. 365.

the temperatures ranged generally from — 21° to —32°, they rose with the arrival of foehn conditions to between — 12° and + 8°. During May, June and July the foehns were characterized by less force of wind and by higher temperatures generally, and the prevailing winds were from the east and northeast instead of from the west and northwest, thus showing that along the coast the cyclones dominate at this period.

In winter at Scoresby Sound, as everywhere in the Arctic fjords, a flat calm region reigns absolutely in the fjords farthest toward the interior. There were none the less several tempests which nearly always came from the west-northwest like foehn winds. . . . At the same time that these foehn blizzards began to let up the temperature mounted extraordinarily and in one case . . . even attained a difference of 23.8° C. within one hour; and simultaneously a hydrometric condition of only 32% was observed" (p. 365).

Stade. — At about the same time studies of the Greenland foehn were being made on the west coast by Stade of the German expedition of 1891–93.[7] The winter station of the expedition was located at the inner end of the Karajak fjord near an outlet from the inland-ice. True foehns and foehn-like winds were observed in great numbers. These were all winds falling off the plateau which arrived suddenly and were unusually warm and dry, but differed from the well-known mountain foehns of the Alps in being of shorter duration and of less violence. Stade found that the foehn winds at the winter station were connected with a low barometer and that this atmospheric depression moved from south to north up the Davis Strait. Already during the approach of the depression there came a large and rapid rise of air temperature, accompanied by a simultaneous fall in relative humidity. The maxi-

[7] Dr. H. Stade, "Ueber Föhnerscheinungen an der Westküste Nord-Grönlands und die Veränderung der Luft-Temperatur und Feuchtigkeit mit der Höhe," Chapter V of vol. 2 (pp. 501–533) of E. von Drygalski, *Grönland-Expedition der Gesellschaft f. Erdk. z. Berlin, 1891–1893,* Berlin, 1897.

mum of air temperature and the minimum both of air pressure and of relative humidity fall almost exactly together. The rise of temperature during a foehn was notably greater during the winter season, being for a single day in February 24° C., and in two days 25° C. (77° F.), whereas in summer its rise never reached 15° C. (59° F.). Moreover, many more foehn winds occurred in winter than in summer.

Stade extended his studies into altitudes of several hundred meters, in one case to about 750 meters, with the result of showing that the fall of temperature gave an average of 1.4° for each 100 meters. This is about .4° in excess of the usually accepted value for the adiabatic of dry air.

As the foehn moves off to the northward the wind swings around from the southeast through the south to the west or even north, and low clouds (stratus and nimbus) or fog drift in. Light winds from the southwestern quadrant practically always accompanied by precipitation bring the foehn to an end. Stade connects the foehns in no way with a glacial anticyclone, but rather with the passage of low-pressure areas up the Davis Strait. We shall see later that these vortices of the anticyclone over the continent and the cyclones over the straits stand in a definite relation to each other.

Wegener. — In northeast Greenland at the winter station of the Danish expedition of 1906–8 (Danmarks Havn in lat. 76° 46′), the foehn is a very common occurrence, blowing off the inland-ice, and there is here a definite type of cloud so well described by Rink (p. 68) called the foehn cloud. Such clouds are produced sometimes in tiers where the strong outward-blowing currents of air from the inland-ice come to slide over relatively stagnant air masses beneath.[8]

[8] A. Wegener, "Meteorologische Terminbeobachtungen am Danmarkshavn," *Med. om Grönl.*, vol. 42, 1911, pp. 10–355; W. Brand and A. Wegener, "Meteorologische Beobachtungen der Station Pustervig," *ibid.*, 1912, pp. 447–562.

Observations at fjord stations. — More or less systematic meteorological observations made throughout a term of years at the various fjord stations on the borders of Greenland, have quite recently been admirably summarized in a work of much importance to students of Greenland physical geography,[9] and the prevailing foehn winds blowing out from the interior taken at stations in order beginning at the northwest are as follows:

Thule, E and SE	Godthaab, E to NE
Upernivik, E	Frederiskshaab, SE
Umanak, E to SE	Ivigtut,[10] E
Jakobshavn, SE and NE	Angmagsalik, NE, N, NW
Egedesminde, SE	Scoresby Sound, WNW [11]
Holstensborg, SE and NE	Mygbugten, NNW [12]
	Danmarks-Havn, WNW [13]

These data we have plotted on the map of Figure 29.

FOEHN EFFECT OF DOWN-SLOPE WINDS AT GLACIER MARGIN

ANTARCTIC

Fricker. — Dr. Fricker in his very valuable monograph upon the origin and distribution of the Antarctic pack-ice,[14] recognized clearly the necessary cooling effect of an elevated snow-

[9] G. C. Amdrup, Louis Bóbe, Ad. S. Jensen, H. P. Steensby, *Grönland, i Tohundrede-Aaret for Hans Egedes Landung udgivet af Kommissionen for Ledelsen af de Geologiske og Geografiske Undersögelser i Grönland,* 2 vols. Atlas, Kobenhavn, 1921 (vols. 60 and 61 of *Med. om Grönl.*).

[10] S. Fritz, "Remarks on the Winds, Clouds, and Auroras on the Southwest Coast of Greenland after 13 Years Observations at Ivigtut," *Meteorologisk Aarbog* for 1882, Copenhagen, pp. x, xi.

[11] W. Jantzen, *Med. om Grönl.,* vol. 17, 1895, p. 365.

[12] From data supplied to the author by Director O. Krogness of Trömso Geofysiske Institutt. See Figure 48, p. 143.

[13] Wegener, *l. c.*

[14] Karl Fricker, *Die Entstehung und Verbreitung des antarktischen Treibeises, Ein Beitrag zur Geographie der Südpolargebiete,* Leipzig, 1893, 208 pages, map.

covered land upon the surface air and the outward flow of the latter. He says:

> From the interior of the land, therefore, the now appreciably cooled air will flow off toward the sea, and as a result be warmed, since the land, as we have seen, attains throughout a considerable elevation. Because of this we must assume that the observed air temperatures are always considerably higher than those in the interior of the Antarctic Continent. As a corollary it would not, upon the other hand, be unwarranted to expect on the coasts of the Antarctic foehn-winds like those of Greenland.

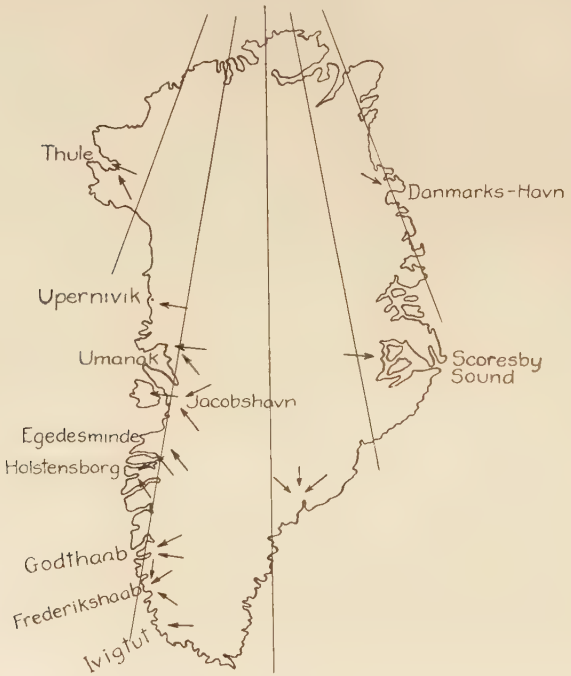


FIG. 29. Map to show the prevailing foehn winds at fjord stations on the margins of Greenland

This was written in advance of any landing upon the Antarctic Continent; and it is therefore an indication of keen insight. Fricker cites observations by Sir James Ross when off Cape

Adare, South Victoria Land, of dry winds blowing directly off the land and thus clearly indicating foehn conditions.[15] It has already been pointed out (p. 11) how he with keen insight saw that an anticyclone must lie over the continent even though there was at the time no direct evidence from the continent itself.

Otto Nordenskjöld. — According to Nordenskjöld foehn conditions in the Antarctic are of less importance than in Greenland.[16] He says:

> Almost around the entire south-polar continent blow predominantly southerly polar winds from the ice-covered interior, and these winds are, for the most part, relatively cold, often indeed very cold (p. 40).
>
> It would be of very especial interest to solve the question why in Greenland and the Antarctic on the borders of the two greatest land-ice masses of the earth, two such entirely different types of climate occur. In Greenland land lies between the ice and the sea; in the Antarctic the ice border comes in direct contact with the sea, but this cannot be the primary cause of the difference. In both regions there is normally an anticyclone over the ice and the prevailing circulation direction of the air masses is from the ice to the sea. From this one would expect that the air would be warmed after the manner of the foehn. In fact, in Greenland the occasionally occurring foehn plays a greater rôle in the country and in the average temperature figures . . . (p. 42).

To the writer, this apparent contrast is explained by the fact that the winter stations of the several British expeditions and of the Swedish expedition as well, were located at a considerable distance from the margin of the inland-ice; and, as was long ago shown by Rink of Greenland, the foehn halts at a very short distance indeed from the ice-margin.[17] Another explanation must serve for the observations made by the Australian expedition, for the two winter stations were in this case on the edge of the inland-ice. In Adelie Land particularly, as Mawson believed, a local permanent anticyclone must be located in the

[15] Fricker, *l. c.*, p. 93.

[16] Otto Nordenskjöld, "Studien über das Klima am Rande jetziger und ehemaliger Inlandseisgebiete," *Bull. Geol. Inst. Upsala,* vol. 15, 1916, pp. 35–46. [17] See also Hann, *Met. Zeitsch.,* vol. 28, 1911, p. 341.

neighborhood, and if upon a relatively low dome of the ice surface, this would fully explain the absence of so great a foehn effect in connection with the blizzards as is the case where the dome is higher and the descent greater. Mawson indeed has inferred a drop of temperature of the blizzard air of 25° F. in its descent from the interior to his base.[18]

In South Victoria Land the British sledging expeditions all found ample evidence of the foehn when they were near the glacier outlets from the inland-ice, and Von Drygalski described foehn conditions in Kaiser Wilhelm Land.[19]

OVERRIDING OF AIR STRATA ON MARGINS OF CONTINENT

Rink. — The rapid increase of the surface gradient towards the margins of the inland-ice brings about an overriding of the air whenever the outstreaming currents of the anticyclone approach blizzard proportions. This phenomenon was described with great clearness and force by Rink in his account of the Greenland foehn as long ago as the middle of the nineteenth century.[20]

Wegener. — Recent observations by modern aërological methods have confirmed Rink's statements. Wegener, in studies carried out at Danmarks-Havn in northeast Greenland at a station more than fifty miles outside the inland-ice margin, found that variable winds were the rule up to an altitude of about one thousand meters, and near this level two lower inversions were encountered almost uniformly. Above these layers, the outstreaming down-slope winds from the inland-ice dominated up to the maximum height to which the ascensions were carried — 2000 meters, and in one instance, 3000 meters.[21]

[18] Mawson, *The Home of the Blizzard,* vol. 1, p. 170.

[19] E. von Drygalski, *Zum Kontinent des Eisigen Südens,* pp. 418–419.

[20] Henrich Rink, *Grönland,* German ed., Stuttgart 1860, pp. 111–112.

[21] Wegener, *Med. om Grönland,* vol. 40, 1909, pp. 1–75, and vol. 42, 1911, p. 326; Brand and Wegener, *op. cit.,* p. 544.

De Quervain. — On the west coast of Greenland De Quervain found similarly by the use of pilot balloons that below 1000 meters there were variable winds, but that outstreaming winds from the interior dominated from one thousand meters up to heights of between 5000 and 9000 meters.[22]

Simpson. — In the Antarctic the British winter station at Cape Evans was apparently too distant from the margin of the inland-ice for any effect of the sort above indicated to be noticed during the summer season. During the winter, however, the temperature curve obtained by the use of registering balloons shows a single strong lower inversion at an elevation of about 1000 meters (see Fig. 45, p. 143).[23]

Barkow. — Barkow on the margins of the inland-ice of the Luitpold Coast in the Antarctic, by means of kites, captive balloons and pilot balloons established the presence generally of a strong lower inversion amounting to about 10° C. near the elevation of 1000 meters.

METEOROLOGICAL CHARACTERISTICS OF THE INTERIOR REGIONS

A region of calms and light airs. — Both over Greenland and the Antarctic once the interior plateau has been reached, shifting light airs or calms appear to be the rule. The experiences of De Quervain and of J. P. Koch within the central area of Greenland, like those of Peary and Rasmussen when they were above 8000 feet of altitude, tell the same story. Says Rasmussen, " On the great plateau — ' pingo ' the Eskimos call it — the weather appears to be mostly calms, and the snow in consequence deep and soft." On his descent toward the east coast, Rasmussen entered in his diary, " We are going downhill now, it seems, and nearing regions that bear more traces of wind. We can see it

[22] De Quervain, *Beiträge z. Physik d. frei. Atmosph.*, vol. 5, 1913, pp. 132–158.

[23] Simpson, *British National Expedition, 1910–1913, Meteorology*, vol. 1, Discussion.

from the snow, which is wind-furrowed now . . . furnishing a valuable aid to direction." [24]

Amundsen during the fortnight which he spent south of latitude 89° S. found a clear sky with light winds except on two days when there were intervals marked by snow flurries. Captain Scott a month later when within the same general region also found shifting light airs for the most part. The sky was often overcast, but the clouds " don't seem to come from anywhere, form and disperse without visible reason." " The meteorological conditions," he says, " seem to point to an area of light, variable winds."

Relative temperatures of snow and overlying air. — One of the most significant series of observations bearing upon this point is that of air temperatures taken by De Quervain during his transection of south-central Greenland (Fig. 28, p. 66).[25] Whereas upon both slopes of the inland-ice the air temperatures between day and night oscillated about 0° C., they no less clearly ranged about — 10° C., rising to — 5° C. in the daytime and sinking to — 15° C. to — 20° C. and more at night. High up on both slopes of the inland-ice the change came with notable abruptness at an altitude on the west slope of 1936 meters and on the east slope of 2250 meters, and the indication is clear that radiation of heat into space from the underlying snow surface is much greater upon the high plateau than it is upon either slope. This implies that the snow tends to have a considerably lower temperature than the air above it, from which air heat would be abstracted and the temperature of the surface layers of air lowered in consequence, at the same time that the surface zone of the snow is warmed.

The sharpness of the margins of the central area of high radiation is certainly most remarkable. It would be interesting

[24] Rasmussen, *l. c.*, p. 335.
[25] *Quer durchs Grönlandseis,* Munich, 1914, p. 137.

to know to what extent these margins are in correspondence with the limits of summer melting of the surface layer of snow, since capacity for radiating heat is known to be dependent in large measure upon this condition and, further, to what extent they correspond to differences of humidity within the air above. Later expeditions should give special attention to this point, as also by studies of the air conditions at moderate distances above the inland-ice surface to determine to what extent these limits of the area of high radiation are in correspondence with the margins of the area of downdraft in the anticyclone.

So far as the writer is aware, the only actual observations which have been carried out upon the temperature of the snow itself within the plateau region of the inland-ice were those of Captain, now Colonel, J. P. Koch,[26] and Dr. de Quervain, which

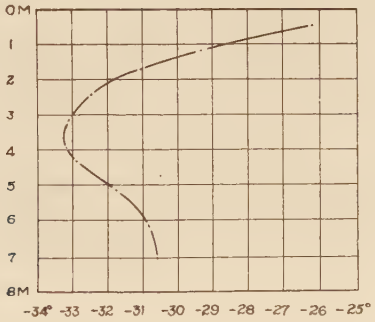


FIG. 30. Temperatures in degrees Centigrade observed within the snow of the inland-ice of the central plateau of Greenland (after J. P. Koch)

observations are therefore of exceptional interest and value.[27] Near the middle of his section J. P. Koch dug a pit in the snow to a depth of eight meters and was able to secure temperatures in the snow to this depth. The results are conclusive in revealing very low temperatures, which reach a minimum of — 33° C.

[26] "Glaciologiske Jagttagelser, i Nordgrönland 1912–13," *Medd. fra Dansk Geol. Fören.*, vol. 4, 1915, pp. 311–361. [27] See the sequel, p. 115.

at a depth of between three and four meters, beyond which point the temperature begins to rise and continues to do so to the extreme depth reached (Fig. 30). It will be noted that the highest of these temperatures close to the surface of the snow is — 26° C., with the surface air temperature at the time — 20° C. The minimum is below even the lowest of the night air temperatures observed by De Quervain during the same season of the year and somewhat to the south upon the plateau. The elevation of temperature by the cooling of the surface air the diagram displays. Colonel Koch has seen in the extreme low temperature of — 33° C. a descending wave of cold from the last winter season.

De Quervain reports, however, having compared the snow temperatures at different slight depths and remarked, " It is interesting to see how exactly the air follows the snow [temperature]." [28]

The differences between air and snow surface temperatures De Quervain found to be much less than these are in the Alps. The maximum difference did not exceed 2° C., " because there was always some wind." Up to midday the snow was found to be 2°–3° C. warmer (in one case 4° C.), but it sinks quite rapidly toward 3 or 4 P.M. By 6 P.M. the snow is 1° C. colder and continues to be so until 4 A.M.

Fogs and in part " dry mists " and precipitation of " frost snow." — Baron Nordenskiöld, when he pushed his way over the inland-ice of Greenland during the summer season of 1883, described at an elevation thought to be above 1500 meters a sky " covered with a thin veil of clouds, through which the sun shone warmly, at times even scorchingly. From time to time this veil of clouds, or haze, descended to the surface of the ice and hid the view over the expanse, but it was, remarkably enough, not wet but *dry*, yes, so dry that our wet clothes absolutely dried in it.

[28] *Quer durchs Grönlandseis*, p. 94.

We have therefore, I consider, witnessed a phenomenon on the inland ice of Greenland which is related to the 'sun-smoke' phenomenon of Scandinavia, *viz.*, what Arago has described under the name 'brouillard sec.'" [29]

Peary and Astrup upon the ice plateau of north Greenland, almost throughout when they were above 8000 feet of altitude, were overwhelmed in "fog." Says Adams:

> The distinctive feature of the homeward journey was the march along and across the summit plateau, about 8000 feet above the sea, during which Peary and Astrup travelled for nearly two weeks in a dense fog which hung to their garments like raindrops. . . . These were the most trying days on the inland-ice. The men could scarcely see the length of their sledges. . . . Men, dogs and sledges were coated with minute opaque white frost crystals. Parhelia, fog-bows and sun-pillars on the fog were continually forming and vanishing, but all the gorgeous pageant could not recompense the travellers for the blanket shroud that enveloped them.[30]

De Quervain reported the air over the plateau to be strongly saturated with moisture, so that at times only the heads of the party would be visible at moderate distances in the bank of mist, and beards, chins, caps, etc., became frozen into solid masses of ice.[31]

Over the boss of the ice-dome of Greenland J. P. Koch found much mist, which in the morning was generally so dense as to hide the sun. The air was so humid that the clothing was constantly wet and was dried with the greatest difficulty.[32]

Fine snow lies over interior region. — All explorers agree that over the interior plateau the snow surface is loose and without wind-furrows — sastrugi. Traveling by sledge is in consequence especially difficult within these areas. The fineness of the snow

[29] "Nordenskiöld's Greenland Expedition," *Nature,* Nov. 8, 1883, p. 41.

[30] Cyrus C. Adams, "Lieutenant Peary's Arctic Work," *Geogr. Journ.,* vol. 2, 1893, p. 311.

[31] De Quervain, *Quer durchs Grönlandseis,* pp. 85, 95.

[32] J. P. Koch, "Unsere Durchquerung Grönlands," *Zeit. d. Ges. f. Erdk. z. Berlin,* 1914, pp. 14–15.

is mentioned by all the explorers who have penetrated the region. Freuchen of Rasmussen's party says in his report:

> The snow lifts and drives before the slightest breath of wind; moving like clouds of vapour. Often it is too fine to be visible at all, until after the lapse of a few minutes men, dogs and sledges are seen to be covered with finely powdered snow.
>
> Thus on the 31st and 1st May, when the wind was extremely violent . . . not a single flake of snow was to be seen, but the air seemed filled with a black fog.[33]

Captain Scott's entries in his diary written on the high plateau near the South Pole again and again call attention to the dampness of the air. All were surprised when the thermometers were inspected that the temperatures were so high. The sun was often shining through a "snow mist."

On the wind encountered near the South Pole, Lieutenant Bowers of Scott's pole party wrote in his meteorological log at latitude 89° 30′ S., as cited by Wright:

> The whole surface was carpeted with a deposit of ice crystals which, while we were there, fell sometimes in the form of minute spicules and sometimes in plates. These caused *almost continuous display of parhelia*. The flags left a month previous by the Norwegian Expedition were practically undamaged, so could not have been exposed to very heavy wind during that time. Their sledge and ski tracks, when marked, were raised slightly, also the dog's footprints, . . . For walking on foot, the ground was all pretty soft and, on digging down, the crystalline structure of the snow was found to alter very little, and there were no layers of crust such as are found on the barrier. The snow seems so lightly put together as not to cohere, and makes very little water for its bulk when melted.[34]

All these observations point strongly to a separation of fine snow crystals from the lower air layers of the interior region of the inland-ice, a process which certainly has even in other regions an importance far greater than has hitherto been accorded to it. Though other examples are not lacking, a quite exceptional instance from his own experience was reported to

[33] P. Freuchen, *Med. om Grönl.*, vol. 51, 1915, p. 346.
[34] Wright and Priestly, *op. cit.*, p. 178.

me by Director von Ficker of the Prussian Meteorological Institute at Berlin, and he has kindly put an account of this experience in writing for publication here. Below is a translation:

STRONG SUBLIMATION OVER AN OLD SNOW COVER

The time between the 16th and the 24th of December, 1904, with my friend A. Defant I spent at the Patscher Kofel cabin 1970 meters above Innsbruck, for the purpose of making measurements of the electricity of the air. During the entire time marked anticyclonal radiation weather with strong temperature inversion prevailed above the valley of the Inn. Below in the valley bottom itself lay ground fog and fog covered also the *Mittelgebirge* terraces on both sides of the Inn. At the time of our ascent we found on the Igls Terrace (elevation about 900 meters) an old snow surface (strongly fused together, hard surface). As I passed the same vicinity on the descent on the 24th December, there lay upon the old snow cover leaf-like crystal snow about a foot deep. Since the time from the 16th to the 24th was completely free from clouds, with exception of the above-mentioned valley fog formations, the thick layer of crystal snow can have been separated out only by sublimation from layers near the earth. In smaller measure, I have often on mountain tours observed the formation of crystal snow through contact sublimation,[35] never, however, in such great quantity as in the above-mentioned case.

H. v. Ficker[36]

In der Zeit vom 16.–24. Dezember 1904 hielt ich mich mit meinem Freunde A. Defant zwecks luftelektrischer Messungen auf dem Patscher Kofel-Schutzhaus 1970 m. oberhalb Innsbruck auf. Während der ganzen Zeit herrschte ausgesprochenes, antizyklonales Strahlungswetter mit starker Temperaturumkehr über dem Inntale. In der Talsohle selbst lag mitunter Bodennebel unt eine niedrige Nebeldecke bedeckte mitunter auch die Mittelgebirgsterrassen beiderseits des Inn. Bei unserem Aufstiege fanden wir auf der Terrasse von Igls (ca. 900 m.) eine Altschneedecke (stark zusammengeschmolzen, harte Oberfläche). Als ich beim Abstieg am 24 Dezember die gleiche Gegend passierte, lag auf der Altschneedecke blättriger Kristallschnee von ca. 1 Fuss Höhe. Da die Zeit vom 16.–24. vollständig wolkenlos war, abgesehen von den erwähnten Talnebelbildungen, kann die dicke Lage vom Kristallschnee nur durch Sublimation aus den bodennahen Schichten ausgeschieden worden sein. In kleinerem Masstabe habe ich auf Bergtouren die Bildung von Kristallschnee durch Kontaktsublimation oft beobachtet, nie mehr aber in solchem Ausmasse wie in dem angegebenen Falle.

H. v. Ficker

[35] The author doubts the propriety of describing this process as sublimation, particularly in view of its loose deposit.

[36] Starke Sublimation auf einer vorhandenen Altschneedecke.

THE CENTRIFUGAL SNOW-BROOM WHICH SHAPES THE CONTINENTAL GLACIER

Snow drift over inland-ice. — As developed in the last section, the snow which comes to lie within the central areas of continental glaciers is of an extreme fineness. As shown by Mawson the snow precipitated at low temperatures consists of minute ice-crystals which are about one-hundredth of an inch (one-fourth millimeter) in diameter.[37] This fine dry drift snow, or *chasse neige,* is lifted and carried in the air by the slightest breath of wind. With even moderate winds, the air is filled to considerable heights by a thick cloud of this material through which little can be seen. To the writer, Sir Ernest Shackleton, in 1909, defended the use of ponies rather than dogs for sledge-animals on the ground that their noses were for much more of the time above this thick drift. Peary wrote long ago of the drift-snow above the inland-ice of North Greenland: [38]

> There is one thing of special interest to the glacialist — the transportation of snow on the ice-cap by the wind. No one who has not been there can have any conception of its magnitude. The wind is always blowing, and blowing always on lines which would be gravity lines from the interior. . . . I have walked for days in an incessant sibilant drift of flying snow, rising to the height of the knees, sometimes to the height of the head. If the wind becomes a gale, the air will be thick with the blinding drift to the height of 100 feet or more. I have seen in the autumn storms in this region, round an amphitheatre of some 15 miles, snow pouring down in a way that reminds one of Niagara. When it is remembered that this flow of the atmosphere from the cold heights of the interior ice-cap to the lower land of the coast is going on throughout the year with greater or less intensity, and that a fine sheet of snow is being thus carried beyond the ice-cap to the ice-free land at every foot of the periphery of the ice-cap, it will perhaps be seen that the above assumption is not excessive.

[37] D. Mawson, "Ice and Snow," in Shackleton's *Heart of the Antarctic,* vol. 2, pp. 335–336.

[38] Peary, *Geogr. Journ.,* vol. 11, 1898, p. 234. See also Peary, *The Secrets of Polar Travel.* New York, 1917, p. 275.

Bernacchi of the *Southern Cross* expedition which wintered at Cape Adare just under the lee of the inland-ice of South Victoria Land, wrote: [39] "Nothing more appalling than these frightful winds accompanied by tons of drift snow from the mountains above, can be imagined."

Mawson at his winter quarters on the edge of the inland-ice of Adelie Land, Antarctic, wrote: [40]

> . . . we led a strenuous existence at winter quarters, buffeting with a sea of drifting snow which poured fluid-thick over the landscape. . . .
> For months the drifting snow never ceased, and intervals of many days together passed when it was impossible to see one's hand held at arm's length. . . . Such weather lasted almost nine months of the year.

To cite a more recent observer, this time describing the inland-ice of Greenland: [41]

> . . . the marginal portions of the glacier were subject to continual storms, with the wind descending the slopes and filling the air with drift-snow.

The fringing snow-drift glaciers. — The centrifugal broom above the inland-ice is, as we have seen, almost continually in operation carrying a portion of the fine snow precipitated within the interior region outward toward the periphery and piling it up about the borders. Since in Greenland, except to the northeast, there is a ribbon of land between the inland-ice and the sea, the sweepings of snow are collected about the margins, where they have been described by Chamberlin from the Ingelfield Gulf region as fringing glaciers.[42] Peary described such a wind-drift border to the inland-ice as a prevalent feature along the northwest and northeast coasts of Greenland.

The Danes in northeast Greenland described "snow-drift

[39] L. Bernacchi in Borchgrevink's *First on the Antarctic Continent*, London, 1901, p. 306.

[40] Mawson, *Geogr. Journ.*, vol. 44, 1914, p. 269.

[41] Rasmussen, *Med. om Grönl.*, vol. 51, 1915.

[42] T. C. Chamberlain, "Glacial Studies in Greenland, VI," *Journ. Geol.*, vol. 3, 1895, pp. 580–581.

glaciers" (*Schneewehen Gletscher*) marginal to the inland-ice, and it was under such snow border that the beautiful cave (*Gnipahöhle*) was followed along the courses of small streams of water (Fig. 31).[43]

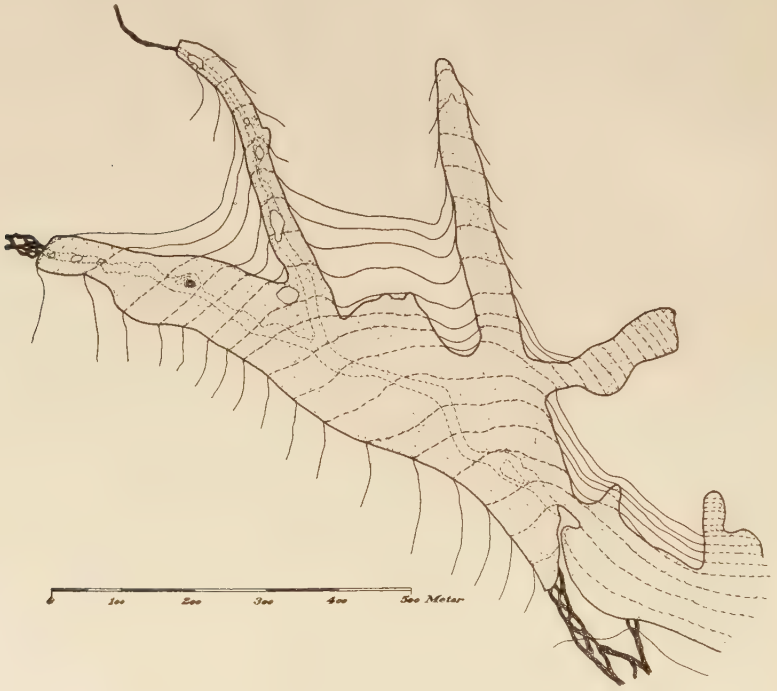


FIG. 31. Map of the Gnipa cave beneath the fringing drift-snow on the border of the inland-ice of northeast Greenland (after Koch and Wegener)

Farther south in northeast Greenland there is a small, and for Greenland an unique, marginal area of what resembles shelf-ice (Fig. 32), over which the flying snow coming down from the

[43] J. P. Koch and A. Wegener, "Die glacialogischen Beobachtungen der Danmark-Expedition," *Med. om Grönl.*, vol. 46, 1912, Chapters VI and VII.

inland-ice plateau lying to the westward, is carried out and dropped upon the sea at places where the stream-lines of the wind become less crowded and where in consequence its velocity falls away.[44] Captain Scott on his first expedition to the Ant-

FIG. 32. The probable unique area of shelf-ice on the borders of Greenland at the foot of the inland-ice (after Trolle)

arctic, drew attention to the vast quantities of drift-snow which in South Victoria Land (where there is no intermediate ribbon of land but an area of shelf-ice) pour off the shelf-ice onto the surface of the sea.

[44] J. P. Koch and A. Wegener, *ibid.*, Chapter I, "Das schwimnende Inlandeis der Jökelbugt."

Sluice-ways for the drift. — Wherever inland-ice is held in by a rampart of mountains, the ice from the interior pushes out in streams (outlets) through the passes in the mountains. These passes occupied by the outlets are sluice-ways for the flow of air, and drift snow pours down these channels to build up great deltas of snow either on the shelf-ice or at the margin of the sea, as the case may be. The form of this delta when over shelf-ice is entirely similar to that of the alluvial fans formed at the mouths of canyons on the inner side of the mountain ranges which hem in the desert. If the sea is near, these deltas, somewhat altered in form, push out as ice-tongues, which are quite common on the borders of the Antarctic inland-ice (Fig. 33). If shelf-ice borders the inland-ice, there are stiffening ribs to the shelf-ice due to these deltas, and these ribs run far out in the shelf-ice mass from the base of the sluice-ways.[45]

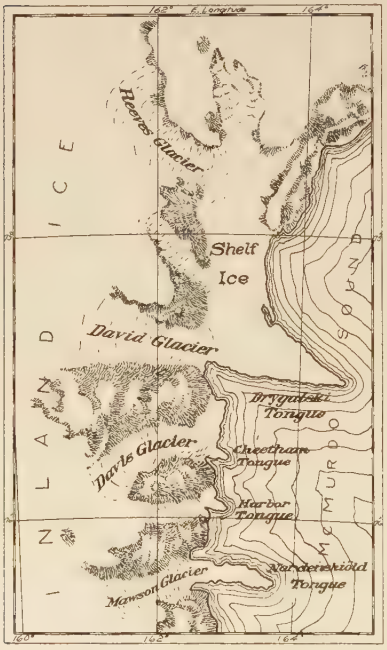


FIG. 33. Map showing outlets from the inland-ice of South Victoria Land and their extensions into the sea as ice-tongues (after Shackleton).

Shackleton on his sledge-journey toward the South Pole toiled over the inland-ice upon the inward journey through deep and mealy snow. In the terrible camp at his farthest south a roaring blizzard from the

[45] T. W. E. David, "Antarctica and Some of Its Problems," *Geogr. Journ.*, June, 1914, pp. 618–619, Fig. 5.

south blew for three days, and on the return journey the surface of the glacier was found swept clean of the mealy snow with consequent excellent sledging conditions over a surface smooth as marble. Over the lower forty miles of the sluice-way of the Beardmore Outlet, however, there was found a great deposit of the snow sweepings which had not been there at the time of the ascent.[46]

Scott on his last expedition was nearly buried beneath the powdery snow which poured down the sluice-way of the Beardmore Outlet accompanied by a high air temperature due to foehn effect; an inundation of snow which held his party in camp for four consecutive days on the surface of the delta and probably wrecked the expedition.[47]

Comparative accretions on interior and on slopes of inland-ice. — Rasmussen has called attention, as already pointed out (see p. 64), to the fact that within the slope portions of his section he found the inland-ice swept clear of snow except for isolated patches; but it was deep under a deposit of fine snow in the interior portion. In view of the experiences of other explorers of the inland-ice, this, so far as it refers to the slopes, must be looked upon as a temporary condition rather than a permanent one. Shackleton's experiences on the inward and outward journeys toward the South Pole are alone convincing as evidence of this.

The best and almost the only data which bear upon the measure of the annual accretions of snow to the continental glaciers and the manner of its distribution, are those supplied by J. P. Koch from his transection of Greenland. Excavations in the snow made near the highest point of his section, indicated that the finely granular surface snow is there abruptly in contact with a more coarsely crystalline subjacent layer which has

[46] Shackleton, *The Heart of the Antarctic,* vol. 2, p. 19.
[47] Scott's *Last Expedition,* vol. 1, 1914, pp. 483–493.

more of the characteristics of *névé* snow, and that the surface layer is the annual deposit. This layer was found to vary from a minimum thickness of 30 cm., or about 12 inches, in the interior to larger values on the slopes — one-half meter near the east coast and a meter toward the west coast. In other words, the annual accretion of snow is on the east coast about one and a half times as great, and on the west coast about three times as great, as it is within the central portion.[48]

There is no doubt a direct relation between the thickness of the snow deposit at any place on the slopes of the inland-ice and the falling of wind velocity due to overriding of lower air layers. This is most striking low down in the glacier outlets where the deltas are formed.

Study of blizzards, the strophs of the anticyclone, show that throughout the earlier stages of the blizzards the fine dry drift snow alone is carried in the air, but at its sudden termination the temperature of the air rises near the margins of the inland-ice and snow is precipitated there. This precipitation may well be due to the blizzard momentum having produced a slight reversal of movement within the anticyclone. During the calm snow separates out over the interior region, and from the outer area this is in part swept outward to the borders of the inland-ice by some later stroke of the thermodynamic centrifugal broom.

This is clearly the process by which the inland-ice has been given its domed surface. The notion that the form of the continental glacier has been the consequence of a process of flow or other internal movement within the mass, like so many other erroneous ideas about these great blanketing masses of ice, has been carried over from mountain glaciers, where form and movements within the mass depend upon the form and the slope of its container of rock. The form of the continental glacier is not

[48] A. Wegener, "Vorläufiger Bericht über die wissentschaftliche Ergebnisse der Expedition," *Zeitsch. d. Ges. f. Erdk. z. Berlin,* 1924, p. 19 (of reprint).

determined by any rock container, except so far as the ice may be dammed back at its margins by a rampart of mountains. Except for the steeper marginal portions, the surface slope of the inland-ice is too flat to bring about fluxion. The thickness of this ice mass in comparison with its expanse may be illustrated by a vertical transection which on a correct scale, if given the thickness of a line drawn by an ordinary pen upon paper, would have a length measured in inches. The flow which unquestionably takes place upon the steep marginal slopes is due to the considerable inclination here of the ice surface, and since this marginal portion during the waxing and waning of the glacier first advances and later retreats over every part of the area covered by the glacier at its culminating period, the distribution of erratic blocks of rock plucked from the bed is adequately accounted for.

CHAPTER VIII

THE HIGHER PORTION OF THE CIRCULATING SYSTEM

THE ALTITUDE TO WHICH THE GLACIAL ANTICYCLONE EXTENDS

Meinardus. — Meinardus, who worked over the meteorological observations made by the German Antarctic expedition of 1902–3, has misinterpreted the observations of westerly winds made by Captain Scott upon the ice-plateau in South Victoria Land lying to the westward of McMurdo Sound. Failing utterly to observe that these winds blow down-slope deviated by earth rotation, he has taken them to indicate that at this level (up to and above 7000 feet) the "overlying circumpolar cyclone" had already been penetrated. If he had been correct, it would be necessary to assume that the anticyclone does not exist at all, for the same down-slope winds were encountered by Scott (and also by Armitage on a separate sledge-journey) from the moment that the parties began to ascend from the Ross Barrier, and this barrier is elevated generally less than 150 feet above the sea. Though not a scintilla of evidence was at hand for this cyclonic circulation, Meinardus wrote in his final report:

> The elevated parts of Antarctica above 2000–3000 meters extend into the great cyclone of the higher latitudes, into the polar whirl and encounter westerly air currents during the entire year. With this verification, which also can be supported further by certain observations from the marginal region, it follows that *the Antarctic anticyclone can, at most, be present as active element in the air circulation only in the lower parts of the South Polar region* [italics in the original]. . . . At the sea-level and on the borders of the inland-ice, that is, within the known coast areas, the anticyclonic conditions do not prevail.[1]

[1] W. Meinardus, *Meteorologische Ergebnisse der Winter-Station des "Gauss," 1902–03, Deutsche Südpolar-Expedition 1901–03,* vol. 3; *Meteorologie I,* vol. 1, 1st Half, Heft II 1911, pp. 332–333.

The best statement of the Meinardus view of the air circulation above the Antarctic is to be found in his article printed somewhat later under the title, "The Results and Problems of the Meteorological Research in the Antarctic." [2]

Recognizing that the icebergs derived in such quantity from the border regions of the Antarctic prove an excess of precipitation over evaporation within the interior region (to which might have been added the stupendous quantities of drift snow which are blown out onto the surface of the sea), Meinardus says:

> The popular view is this, that the entire south polar region is covered over by an anticyclone, an area of high pressure. This view is based on the existence of the easterly winds within the border region of the Antarctic, and, further, on the actually observed increase in pressure toward the south. We have, however, already in what has gone before proven that the border region of the Antarctic is not under anticyclonal air pressure conditions, but under a cyclonal one. The Antarctic anticyclone, if it is present, can take in only the minor part of the Antarctic. . . . In this case, however, it sets up a difficulty to explain the snow covering of the inner portion, which we must include; for in an anticyclone the air flows in in the upper layers, it then descends, becomes relatively dry, and flows outward below in all directions. Unfortunately, in this sort of air movement no precipitation can occur which would be greater than the evaporation. . . . On the contrary, in anticyclonal regions the evaporation is greater than the precipitation, for the air which comes down from above and is warmed dynamically, is relatively very dry and now by the outward streaming movement it will take up moisture to itself from the earth's surface and remove it from the realm of the anticyclone. In our case a drying out and freedom from snow of the interior south polar region must be the consequence (pp. 30–31).

Meinardus then continues on the basis of a computed average height of the Antarctic Continent of 2000 meters (for which no data are at hand) and says:

> The Antarctic anticyclone, of which to the present has been the talk, is an air pressure condition which belongs only to the lower layers of the atmosphere. It comes out clearly only in the distribution of air pressures at the level of the sea. On the other hand, on account of the low tempera-

[2] W. Meinardus, "Aufgaben und Probleme der meteorologischen Forschung in der Antarktis," *Geogr. Zeitsch.*, vol. 20, Heft 1, Leipzig, 1914, pp. 18–34.

ture of the south polar region, the vertical falling off of air pressure must be so rapid that above a certain height the air pressure over the south polar region is not higher, but lower, than in its neighborhood. Above the lower anticyclone, there lies then a cyclone, the so-called "Polar Whirl" of the general circulation of the atmosphere. . . . (pp. 31–32).

Shaw. — Sir Napier Shaw in 1904, upon the basis of the maps published in Hann's *Meteorologie* (on which the isobars are made to take their course without deviation over the inland-ice of Greenland as though they were crossing an expanse of sea), has argued for circumpolar whirls taking their direction from west to east within the lower strata of the atmosphere.[3] A few years later in his preface to the volume on meteorology of the Scott expedition, he wrote:

> The Antarctic anticyclone, if it exists, is a comparatively superficial effect attributable to the surface cold. But to give an easterly wind there must be sufficient thickness of cold air to reverse the gradient of the upper air, which as shown by the smoke of Erebus and by cloud observations at high levels, is poleward; 5000 feet is probably an ample allowance for the thickness of the cold surface cap which has an east to west rotation. In order to give a resultant gradient for easterly winds, the gradient of the cold surface layer must exceed that of the westward moving layer up above. One requires, therefore, a rapid *change of pressure*[4] in the surface layer, and with that we should expect to find a *rapid temperature gradient poleward.*[5]

Hann. — It will be remembered that Professor Hann in his correspondence with Mr. Robert H. Scott, before Captain Robert F. Scott set out upon his first Antarctic expedition, denied the existence of any anticyclone whatever above the Antarctic Continent.

When the report of Meinardus appeared, he adopted Hann's viewpoint, *viz.*, that a shallow anticyclone exists above the An-

[3] W. N. Shaw, "On the General Circulation of the Atmosphere," *Proc. Roy. Soc.*, vol. 74, 1904–5, p. 25.

[4] The italics are his. It is to be noted that as Sir Napier takes no account of the topography of the inland-ice, he has made the same error as Meinardus in interpreting the wind directions.

[5] *International Antarctic Expedition, 1901–04, Meteorology,* Pt. I, 1908, p. xiii.

tarctic region with the traditional circumpolar cyclone over it. His view is best stated in an extended review of the Meinardus monograph which was published in Hann's own meteorological journal.[6]

Citing Meinardus's controversial affirmation that there is a cyclonic east wind zone as a border to the Antarctic anticyclone, Hann declares: "This is one of the most important results of the newest meteorological observations within the south-polar region." "We must conclude," he says, "that the south-polar region considered as a whole resembles those regions in which the cyclonic air-pressure condition dominates over the anti-cyclonic air-pressure condition. . . ."

"In the central part of an anticyclone evaporation exceeds precipitation; it is a region of consumption and not one for nourishment of snow and ice deposits. In the center of a permanent anticyclone the beds of snow and ice must in consequence be entirely lacking, and to this conclusion we should come for the interior of the Antarctic Continent." But seeing that this has been contradicted by the observations of Shackleton and Scott, Hann adopts the viewpoint of Meinardus that an encircling cyclone to the anticyclone overlies it upon a domed surface and as the continental surface rises higher its upper levels project upward into the cyclone above and so secure nourishment. Hann cites also with high approval the *höchstwahrscheinlich* estimate of Meinardus of 2000 meters as the mean height of the Antarctic Continent,[7] notwithstanding the fact that the interior has even today been penetrated for relatively short distances about the Ross Sea and in Adelie Land only (see Fig. 24, p. 62). The basis for an estimate of any

[6] J. Hann (referat), W. Meinardus, "Die meteorologischen Ergebnisse der Deutschen Südpolar-Expedition 1902 bis 1903, II," *Meteorol. Zeitsch.*, vol. 28, 1911, Heft 8, pp. 337–349.

[7] W. Meinardus, "Die mutmassliche mittlere Höhe des antarktischen Kontinents," *Pet. Mit.*, vol. 55, 1909, pp. 304–309, 355–360.

value whatever does not of course exist. After some tabulated results giving the average air-pressure at points, *all of which are remote from the inland-ice,* Hann concludes:

> From the above we find: The Antarctic anticyclone is under the above considerations winter and summer alike no longer to be found at an altitude of 2000 m. and has already at this level been replaced by the polar cyclone. In January it is still present at 2000 m., it reaches in this month about to 3000 m. For December and February it is about the same. It is therefore assumed that the anticyclone is developed in January about as much as in July. Should, however, the air-pressure in January be somewhat lower, then in January the anticyclone would not reach the level of 2000 m.
>
> This much is in any case certain, that the anticyclone in all months is a phenomenon of the lower air layers and in summer reaches up at highest to 2000 m.
>
> The Antarctic anticyclone is, in consequence, present only in the northern portions of the South-polar region as an active element of the air circulation, that is to say, within the marginal zones.[8]

David. — In his discussion of the meteorology of the Shackleton Antarctic expedition, David, as already pointed out, shows an anticyclone lying above the Magnetic Pole Plateau of South Victoria Land, but with a cyclone above it. It would appear that David has been led to adopt this view because otherwise he is unable to account for the nourishment of the inland-ice. Taking no account of the moisture locked up in the ice-particles of the cirri and other high-level clouds, but brought down to the surface and vaporized and in turn separated out near the surface, David avers of the anticyclone that it is " a region of starvation, not of alimentation of ice and glaciers," thus adopting the views of Hann and Meinardus (see pp. 94–96).

Barkow. — It is a great relief to turn away from the speculations of meteorologists concerning high-level circulations based on no direct pertinent observations whatever, and to take up actual soundings in the free atmosphere undertaken by means of self-registering instruments carried by kites and balloons.

[8] *Op. cit.,* pp. 347–349.

Barkow, the meteorologist of the Filchner expedition to the Luitpold Coast and Weddell Sea, Antarctic, sent up kites, captive balloons and pilot balloons, the latter to altitudes in some instances much above the ceiling of the troposphere,[9] which was here found to be between the altitudes of 6500 and 9000 meters. The balloons were sent up both from the ship when lying off the Luitpold Coast, and from a station on shore near the margin of the inland-ice. Almost throughout these observations by Barkow reveal a strong lower inversion which was generally in excess of 10° C. and which was found to extend up to an altitude of 1000 meters. Similar inversions have by like methods been observed near the margin of the inland-ice of Greenland on the west coast and on the northeast coast. They are of course explained by the cold air from the plateau sliding over relatively stagnant air masses outside the inland-ice margins.

A pilot balloon sent up in February was followed to the height of 17,200 meters. As a result of this observation and others it was clear that, whereas easterly and northeasterly winds (slope-winds from the inland-ice) dominated up to an altitude of 9000 meters, at that level the wind direction suddenly veered through 180° — the wind now came steadily from the southwest. The place of this observation was in lat. 77° 45′ S, long. 34° 40′ W, or just off the margin of the inland-ice. The lower winds, therefore, must be regarded as constituting the centrifugal lower portion of the anticyclonic vortex only slightly deviated by earth rotation (see Fig. 27, p. 65). The reversed winds above 9000 meters would constitute the indraft toward the central area of the anticyclone — the upper portion of the same vortex, the direction of the plateau being to the northeastward of the station.

[9] E. Barkow, "Vorlaüfiger Bericht über die Meteorologische Beobachtungen der deutschen Antarktischen Expedition 1911–1912," *Veröffentl. d. k. preusz. meteorolog. Instituts,* No. 265 (Abh., vol. 4, 1913, No. 11), pp. 1–11.

Barkow's conclusions are of the utmost importance. He says:

> The maximum heights go many times above the upper limit of the troposphere to be expected in polar regions. As indicator of the stratosphere there can here serve only the so frequently observed change of the wind direction or a sudden falling off of the wind velocity. In the case of some ascents these changes are so distinct that I must believe this layer of sudden change is the boundary of the upper inversion (p. 8).
>
> Of the utmost significance for the question of the general air circulation within the entire south-polar region, are the east winds of the Antarctic. Meinardus, for example, on the basis of his work has come to the conclusion that these east winds are a phenomenon of the lowest air layers up to about 2000 meters of altitude, above which dominates then the great polar whirl with essentially west winds. Here now we have for the first time material facts by which these theories can be tested (p. 9).

After giving examples Barkow continues:

> Here we have east wind up to 6400 meters; in this altitude the wind turns sharply to the south, and, further, to the southwest. In this sharp turning is indeed once more to be seen the entry of the balloon into the stratosphere, even if this height seems quite low for it (p. 10).[10]

Wegener. — These observations were carried out with kites and captive balloons and did not extend above 2000 meters, except in a few instances when they attained 3000 meters. Up to the altitude of about 1000 meters there were found to be variable winds, and two strongly marked lower inversions occur almost uniformly above 1000 meters. The strong winds slipping down off the inland-ice dominate absolutely in the higher levels. The wind-rose shows that the strong winds come from the northwesterly quadrant down the ice-slope but are deviated to the right by earth rotation. Foehn effects and foehn clouds are characteristic. Two meteorological stations of the expedition were established, the main station of Danmarks-Havn and that of Pustervig, the latter quite near but outside of the ice-margin, and the main station some fifty miles farther out and on the coast. Wegener does not recognize the glacial anticyclone above

[10] See also p. 136 of Chapter IX.

the inland-ice, though he speaks of the high-pressure area, and all his observations are in harmony with those made elsewhere in Greenland. He points out that all weather disturbances are in the main controlled by the down-slope winds of the inland-ice. The reading of his monographs gives the impression that he was somewhat unfamiliar with the work of others upon inland-ice whether in the Arctic or the Antarctic.[11]

De Quervain and Stolberg. — At a number of stations near the borders of the inland-ice of western Greenland, De Quervain and Stolberg in 1909 carried out ascents of pilot balloons during spring and early summer, attaining extreme heights which were in some instances in excess of 10,000 meters (6 2/3 miles), and in one instance reached the height of 16,000 meters. In 1912–13 Dr. Jost and Dr. Stolberg supplemented these earlier observations by a second series carried out during the winter season.[12]

Below the level of 1000 meters these observers found variable light winds to be characteristic, and these were evidently controlled by local surface conditions. The outward-flowing currents from the inland-ice first make their appearance in force near the 1000 meter level, and they control the circulation up to an altitude of between 5000 and 9000 meters. Above that level there is noted a change in direction from the southeast to inward-blowing currents from the southwest. The clockwise deviation of winds over this hemisphere allows us to conclude that the southeasterly winds started near the summit of the ice-dome as a more easterly wind which has in its descent veered to the

[11] A. Wegener, "Drachen- und Fesselballon-aufstiege ausgeführt auf der Danmark-Expedition 1906–08," *Med. om Grönl.*, vol. 40, 1909, pp. 1–75; "Meteorologische Terminbeobachtungen am Danmarks-Havn," *ibid.*, vol. 42, 1911, pp. 124–355; W. Brand und A. Wegener, "Meteorologische Beobachtungen der Station Pustervig," *ibid.*, 1912, pp. 445–562.

[12] A. de Quervain, "Gleichzeitige Pilotaufstiege in Westgrönland und Island, Veranstaltet durch die schweizerisch-deutschen Grönland-Expedition und das dänische meteorologische Institut," *Beitr. z. Physik d. frei. Atmosphäre*, vol. 5, 1913, pp. 132–158; A. de Quervain, *Quer durchs Grönlandseis* (A. Stolberg, "Ein Winter in Grönland," pp. 171–196).

southeast. The higher-level inblowing winds likewise presumably will arrive over the plateau coming from a more westerly direction, and hence opposed in direction to the surface currents within that region.

From the foregoing observations, derived as they are from points near to both the great continental glaciers, any further discussion of a cyclone assumed to overlay the glacial anticyclone, or of a "circumpolar whirl," "circumpolar cyclone," or "polar calm," of the sort visualized by Ferrel and developed by Hann and Meinardus seems superfluous.

MOVEMENTS OF HIGH-LEVEL CLOUDS IN RELATION TO THE ANTICYCLONE

The upper portion of the anticyclone vortex. — The observations carried out by Barkow and by De Quervain and his associates have indicated that the glacial anticyclone is extended upwards to the neighborhood of the ceiling of the troposphere. This ceiling is in the opinion of meteorologists the upper limit of the convectional process within the atmosphere.[13] The outdraft of air below must in this vortex be fed by an indraft above (see Fig. 18, p. 51). The high-level clouds, mainly cirri and their variations, which float below the troposphere ceiling, and the alto-stratus and alto-cumulus clouds, should therefore be examined with regard to their directions of movement as parts of the anticyclonic vortex.

The cloud-types of the inland-ice. — Nansen on his first crossing of Greenland found for the entire route that the most frequently observed cloud-types were, first, the cirri, then cumulo-stratus clouds, and next the cirro-stratus. Cumulus clouds were

[13] W. J. Humphreys, "On the Physics of the Atmosphere," *Journ. Franklin Inst.*, March, 1913, p. 218; W. N. Shaw, "Principia Atmospherica, A Study of the Circulation of the Atmosphere," *Proc. Roy. Soc. Edinb.*, vol. 34, Pt. I, 1914, p. 82.

not once observed.[14] Bernacchi reporting upon the clouds observed at the winter quarters on Cape Adare, Antarctic, which were located close under the lee of the inland-ice, found that whenever the almost constant low grey mists allowed the sky to be seen, there were only a few high clouds and isolated cirri.[15]

Over the inland-ice the most abundant clouds have in general been found to be the cirri and their variations. The late Sir Ernest Shackleton emphasized especially the cirri as the most important clouds above the inland-ice plateau of the Antarctic.[16] Above the Magnetic Pole Plateau David observed especially the cirri, which were drawn out in the "Noah's Ark" form, these bands taking their course across the sky in a sweeping curve.[17]

Observations from South Victoria Land. — After the observations of Bernacchi at Cape Adare, which were mentioned above, almost the first observations of value upon the movements of the higher air currents near the inland-ice are those of the British National Antarctic Expedition under Scott. The winter quarters, though located at a considerable distance from the inland-ice margin, possessed the great advantage of having always in view during clear weather the vapor cloud ascending from the active volcano of Mount Erebus with a crater rim over 13,000 feet in altitude. The report by Curtis upon these observations of upper-air currents is therefore of very special interest.[18] From Figure 34, reproduced from Curtis's report, it will be seen that the high-level clouds, all estimated to be at altitudes in excess of 20,000 feet, have directions almost directly opposed to those

[14] H. Mohn, *Pet. Mit.,* Ergänzungsh. 105, 1892, p. 48.

[15] L. Bernacchi in C. E. Borchgrevink's *Through the First Antarctic Night,* 1900, p. 416.

[16] Personal communication to the writer.

[17] David in Shackleton's *Heart of the Antarctic,* vol. 2, pp. 168, 171, 175. See also Freuchen, *Med. om Grönl.,* vol. 51, 1915, pp. 413–425.

[18] R. H. Curtis, *Distribution of Air Currents of Various Levels at "Discovery's" Winter Quarters, South Victoria Land, National Antarctic Expedition 1901–04, Meteorology,* Pt. I, London, 1908, p. 496.

of the surface currents,[19] and that the vapors of Mount Erebus take a direction intermediate between those of the upper clouds and the surface winds. Scott's later expeditions supplied additional data concerning upper-cloud directions, and these have

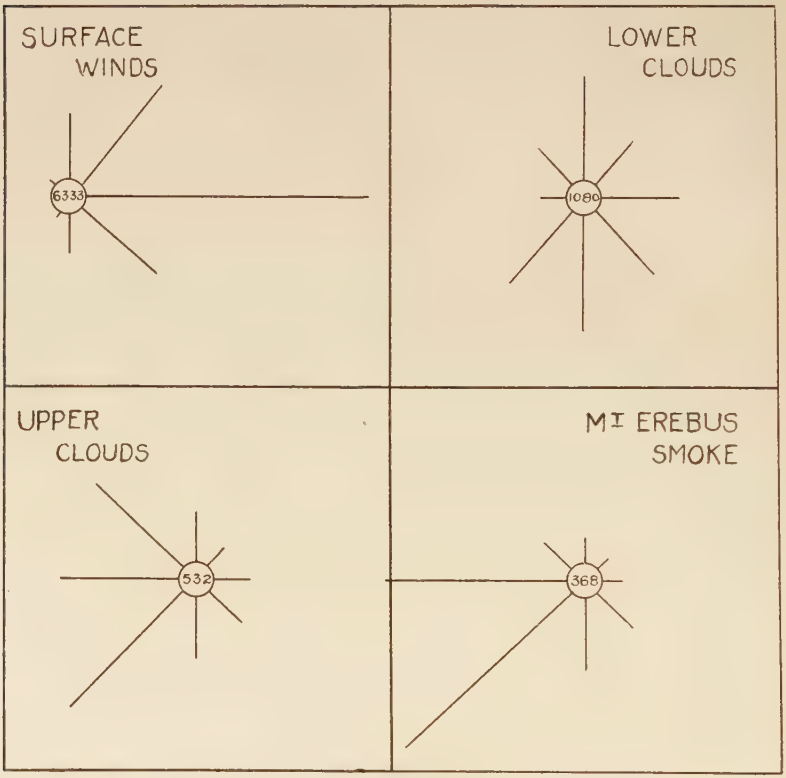


FIG. 34. Roses showing directions of surface winds, of clouds, and Erebus vapors near the British winter quarters on McMurdo Sound, Antarctic (after R. H. Curtis)

[19] These surface winds are usually more from the southeast than the normal winds which appear to be more southwesterly (cf. Debenham, *The Physiography of the Ross Archipelago, British (Terra Nova) Expedition 1910–13*, 1923, London, p. xii).

been summarized by Simpson, the meteorologist of the expedition.[20]

At Cape Evans, the average direction of the high clouds is from the northeasterly quarter (N. 27° E.), more or less opposed to that of the surface winds. At Cape Adare the average direction of the high clouds is from the northwesterly quadrant (N. 23° W.). This latter station is just under the lee of the inland-ice margin, the plateau rising in a direction about southeast from the station. Deviation, which is here counter-clockwise, would bring these directions more nearly into opposition.

Observations from Kaiser Wilhelm Land, Antarctic. — In Kaiser Wilhelm Land observations carried out by the German expedition under Von Drygalski showed that the mean direction of the higher clouds was from N. 18° E., and those of medium height from N. 74° E., whereas the mean direction of the surface winds at the station of the *Gauss* (out on the sea-ice of Posadowsky Bay) was N. 101° E.[21]

Study of motions of high-level clouds about Greenland. — The attempt is here made to assemble the data relating to the motions of high-level clouds about the margin of Greenland and over land masses at other points of observation not so remote as to lose significance. The assembled data are represented in Figure 35.

A generalization of Hildebrandsson is that "in the region of the higher clouds, Ci and CiS, the direction of the wind is on the average from west to east within the temperate zone, and from east to west in the tropical zone."[22]

[20] G. C. Simpson, D. Sc., "Chief Results of the Meteorological Observations Made on Capt. Scott's British Antarctic (*Terra Nova*) Expedition 1911 and 1912," *Quart. Journ. Roy. Meteor. Soc.*, vol. 40, 1914, pp. 221–227.

[21] Hann in review of Meinardus, *Met. Zeit.*, vol. 28, 1911, p. 338.

[22] H. Hildebrand Hildebrandsson, "Résultats des Recherches Empi-

FIG. 35. Map of the region about the continent of Greenland to show observed prevailing directions of upper cloud movements. The short arrows over the inland-ice of Greenland refer to observed surface-wind directions, and these betray the centrifugal distribution already described. The longer arrows give the prevailing direction of movement of the upper clouds compiled for winter (W) and summer (S) separately. The clouds of the winter season show a greater constancy of direction. In those cases where the upper clouds of the summer season betray no constancy of direction, the arrow is omitted. All arrows fly with wind or cloud.

Upper-cloud data are available from Greenland itself — Upernivik [23] and Godthaab,[24] both on the west coast — and from a considerable number of stations distant from 150 to 400 miles which are distributed on all sides of the continent except the north and south. To the eastward and northeastward lie the stations of Bossekop,[25] Franz Joseph Land,[26] both somewhat remote; and Iceland,[26] Jan Mayen,[26] and Spitzbergen.[26] To the northwestward, westward and southwestward, observations on prevailing directions of the upper clouds are available from Fort Conger [27] (Grant Land), Ellesmere Land,[28] Kingua Fjord [29] (Baffin Land), Nain [30] (Labrador), as well as from various stations in Newfoundland (see below).

The observations of upper-cloud motion carried out during the drift of the *Fram* through the Polar Sea, have been assembled and summarized by Mohn [31] for the entire drift, which extended through 140° of longitude and over some years of time. For the

riques sur les Mouvements Généraux de l'Atmosphère," *Nova Acta Reg. Soc. Scientiarum Upsaliensis,* Ser. IV, vol. 5, 1918, No. 1, pp. 1–50, pls. V.

[23] H. H. Kimball, "The General Circulation of the Atmosphere, Especially in Arctic Regions," *Month. Weath. Rev.,* Sept., 1901, pp. (of reprint) 1–28, figs. 1–2.

[24] *Observation Internationale Polaire, Expédition Danoise,* tome II, IIe livraison, Ière partie, pls. 29–41, Inst. Mét. de Danemark, Copenhagen, hagen, 1889.

[25] *Beobachtungs-Ergebnisse der Polarstation Bossekop in Alten,* in *Auftrage des königl. Norw. Kultus-Ministeriums, Christiania,* 1887–1888.

[26] H. H. Hildebrandsson, *op. cit.*

[27] Adolphus W. Greely, *Rept. on the Proceedings of the U. S. Exploring Expedition to Lady Franklin Bay, Grinnell Land,* vol. 2, Washington, 1888, pp. 318–365.

[28] H. Mohn, *Meteorology, Rept. Second Norwegian Arctic Expedition in the "Fram," 1898–1902,* No. IV, pp. 334–335.

[29] *Die Beobachtungs-Ergebnisse des deutsch Stations,* Bd. I, *Kingua Fjord und die meteor. Stationen II Ordnung in Labrador* (Nain), Berlin, 1896.

[30] H. H. Kimball, *op. cit.*

[31] *The Norwegian North Polar Expedition 1893–1896, Scientific Results,* edited by Fridtjof Nansen, vol. 6, London, 1905, *Meteorology,* by H. Mohn, "Observations" on pp. 25–253.

question here under consideration it seems best to examine these data for the summer and winter months separately, since the vigor of the anticyclone is so much greater during the winter season. It is also necessary to neglect those observations which were made at points too remote from the Greenland Continent. When the observed directions of motion for the upper clouds are assembled in this manner, it appears that in the western portion of the area traversed by the *Fram* the cloud motions are variable during the summer, but move toward the southwest (Greenland) during the winter season (Fig. 36). The mean

FIG. 36. Directions of cloud movements observed from the *Fram* during its first Arctic cruise (based on Mohn and Nansen)

direction for the winter has been entered upon the map of Figure 35, p. 104.

In this connection the kite ascensions carried out over the Greenland Sea by Hergesell from the yacht of the Prince of Monaco in 1906 have very special interest.[32] In general it was found that the velocity of the wind increased rapidly with altitude and that a stratum relatively quiet separated the lower local winds from those above a level of ten kilometers from the ground. These upper winds had a general direction always with

[32] H. Hergesell, "Die Erforschung der freien Atmosphaere über dem Polarmeer," *Beitr. z. Physik der fr. Atmosph.*, vol. 2, 1906–8, pp. 96–98.

a strong component directed toward the west and with velocities between 15 and 20 m.p.s.

The Meteorological Service of Canada has for some years carried out observations upon directions of cloud motions, and these data have been courteously placed at my disposal for purposes of study by Sir Frederic Stupart, the director of the Service. Those made on high-level clouds at a number of stations on the Island of Newfoundland number nearly 1000 individual observations, and when these are assembled they are found to agree well as between the several stations. The composite result for the Island of Newfoundland, as I have compiled it from these data, I am permitted by Director Stupart to publish, and it appears on the map of Figure 35.

As a result of all these assembled data relating to the motions of the high-level clouds about Greenland, it appears that at the distant stations in Norway and on Franz Joseph Land the influence of the glacial anticyclone in turning aside the cloud currents is slight, if at all. Upon the other hand, at the nearer stations on Iceland, Jan Mayen, Spitzbergen and the area northwest of Spitzbergen, cloud motions within the upper levels show an indraft towards the Greenland Continent in all cases during the winter season and rather generally during the summer also. On the northwest, west and southwest of Greenland, the cloud directions indicate motion likewise toward the Greenland Continent, but these data are less significant, since they correspond to the general law of motion determined by Hildebrandsson for the temperate zone. The striking exception to his general law which characterizes the area on the east of Greenland, was in fact noted by Hildebrandsson, who explained it thus:

> One sees that there are some stations, above all Reykjavik on the south coast of Iceland, where the course of the clouds is from east or northeast. This exception is easily explained. To the south of Greenland and Iceland is situated the great minimum barometric mean, grooved almost without cessation by the low areas passing from west to east. To the

northward we have the vast cold land of Iceland and that of Greenland, always covered with ice, above which there is frequently, above all in winter, a barometric high pressure. But in such a situation, we have seen above, the depressions are strongly developed and closed above even to the altitude of the cirri. The passage of such strong depressions being practically continuous, it follows that one sees at these stations the cirri take their course in general from the east in spite of the course of the minima from the west to east.[33]

[33] *Op. cit.*, p. 18.

CHAPTER IX

CORRELATION OF MATERIAL FROM THE LATEST PERIOD

BEARING OF THE NEW MATERIAL MADE AVAILABLE SINCE 1915

Outline survey. — A considerable body of data bearing upon the problem of the air circulation above the continental glaciers has become available since 1915. The only important expeditions that have been carried out in the Greenland region are those of Dr. Lauge Koch in 1921 [1] and 1923, mainly in north Greenland and these not primarily for either glaciological or meteorological purposes (Fig. 37). In the Antarctic area one expedition also has contributed some data bearing on the glacial anticyclone, viz., that of the late Sir Ernest Shackleton, who discovered the Caird Coast of the Antarctic Continent fronting upon the Weddell Sea and lying between Coats Coast and Luitpold Coast (see Fig. 42, p. 124).[2] Some final monographs of the very first importance which treat of earlier expeditions have appeared.

For Greenland we have the final report by Mikklesen on his expedition of 1909–12 [3] in search of Mylius Erichsen and com-

[1] "Jubilæumsexpeditionen Nord om Grönland," *Geografisk Tidskrift,* vol 26, 1922, pp. 183 (edited by the Secretary of the Danish Geographical Society); "Resultaterne af Jubilæumsekspeditionen Nord om Grönland, i 1921," *Naturens Verden,* Feb., 1923, pp. 49–76, 4 maps.

[2] R. C. Mossman, "Meteorological Results of the Shackleton Antarctic Expedition, 1914–1917 (Weddell Sea Party): Preliminary Notice," *Quart. Journ. Roy. Meteorol. Soc.,* London, vol. 47, Jan., 1921, pp. 65–70 (see also various special monographs by Wordie in *Trans. Roy. Soc. Edinb.,* vols. 52 and 53).

[3] Ejnar Mikkelsen, "Alabama-Expeditionen til Grönlands Nordostkyst 1909–1912," *Med. om Grönl.,* vol. 52, 1922, pp. 295, many maps and plates (English text).

LINCOLN SEA
GRANT LAND
GRINNELL LAND
KANE BASIN
SMITH SOUND
INGLEFIELD GULF
VICTORIA FIORD
ROBESON CHANNEL
KENNEDY CHANNEL
HALL BASIN
Humboldt Glacier
Lockwood I.
DeLong Fiord
Shepard Osborn
St. George Fiord
Cape Morris Jesup
Cape Hatteras
Cape Calhoun
Cape Constitution
Cape Alexander
Cape Isabella
Cape Sabine
Cape Parry
Cape Frazer
Cape Bryant
Cape Hilgard
Cape Lieber
Cape Union
Cape Faraday
Cape Rawlinson
Cape Tennyson
Cape Hawkesbury
Cape Lupton
Cape Lyon
Cape Sumner
Cape Isachsen
Cape Sheridan
Cape Columbia
Cape Joseph Henry
Cape Richardson
Cape Rutherford
Cape Collinson
Cape Clarence
Cape Bryan
Cape Hotham
Cape Jackson
Cape Hawks
Cape Alexandra
Cape Albert
Cape Victoria
Cape Albert Edward
Cape Prince Alfred
Cape Prince Arthur
Cape Prince Leopold
Cape Prince Patrick

panions who were lost in 1907, and that by De Quervain and Mercanton on the Swiss Greenland expedition of 1912–13.[4] Though the final report of Captain J. P. Koch on his transection of Greenland in 1913 has not yet been published, a narrative account from which many valuable data may be gleaned is now available.[5]

The sledge routes of the complete series of expeditions in Greenland are set forth on the map of Figure 38. On Figure 39 the profiles derived from the various transections, all reduced to a common scale, are reproduced together for purposes of comparison and, further, to afford a more comprehensive view of the domed surface of the snow-ice mass upon which the glacial anticyclone depends.

Treating of the meteorological conditions over the Antarctic continental glacier, we have two final reports from the Last Scott Expedition: that of Simpson on the meteorology [6] and that of Wright and Priestley on the glaciology.[7] There has appeared, further, the posthumous final report of Barkow on the meteorology of the second German expedition to the Antarctic (Filchner), a work of very great value.[8]

[4] Alfred de Quervain and P.-L. Mercanton, "Ergebnisse der schweizerischen Grönlandexpedition," *Denksch. d. schw. Naturf. Gesell.*, vol. 53, 1920, pp. 402, many maps, plates and figs. See Charles F. Brooks, "The Ice Sheet of Central Greenland, A Review of the Work of the Swiss Greenland Expedition," *Geogr. Rev.*, vol. 13, 1923, pp. 445–453, and "Winds and Weather of Central Greenland: Meteorological Results of the Swiss Greenland Expedition," *Month. Weath. Rev.*, May, 1923, vol. 51, pp. 256–260.

[5] J. P. Koch, "Durch die weisse Wüste, Die dänische Forschungsreise quer durch Nordgrönland 1912–13," Deutsche Ausgabe besorgt von Prof. Dr. Alfred Wegener, Berlin, 1919, pp. 248, 158 figs. and 2 maps.

[6] G. C. Simpson, *Meteorology, British Antarctic Expedition 1910–1913*, Calcutta, 1919, vol. I; *Discussion*, pp. 326, figs. and pls., vol. II; *Weather Maps, etc.*, vol. III. Tables, London, 1923, pp. 835.

[7] C. S. Wright and R. E. Priestley, "Glaciology," *ibid.*, London, 1922, pp. 487, pls. 291, pocket of maps.

[8] E. Barkow, "Die Ergebnisse der meteorologischen Beobachtungen der deutschen Antarktischen Expedition 1911–1912," herausgegeben von K. Knoch, *Veröffentl. d. preusz. meteorol. Instituts* (v. Ficker), Nr. 325, Abh., Bd. VII, Nr. 6, Berlin, 1924, 166 pages.

FIG. 38. Map of Greenland, showing all sledge-routes over the inland-ice

Dr. Lauge Koch's truly remarkable studies made mainly in northern Greenland are not yet (March, 1925) available in print with the exception of a few preliminary articles.[9]

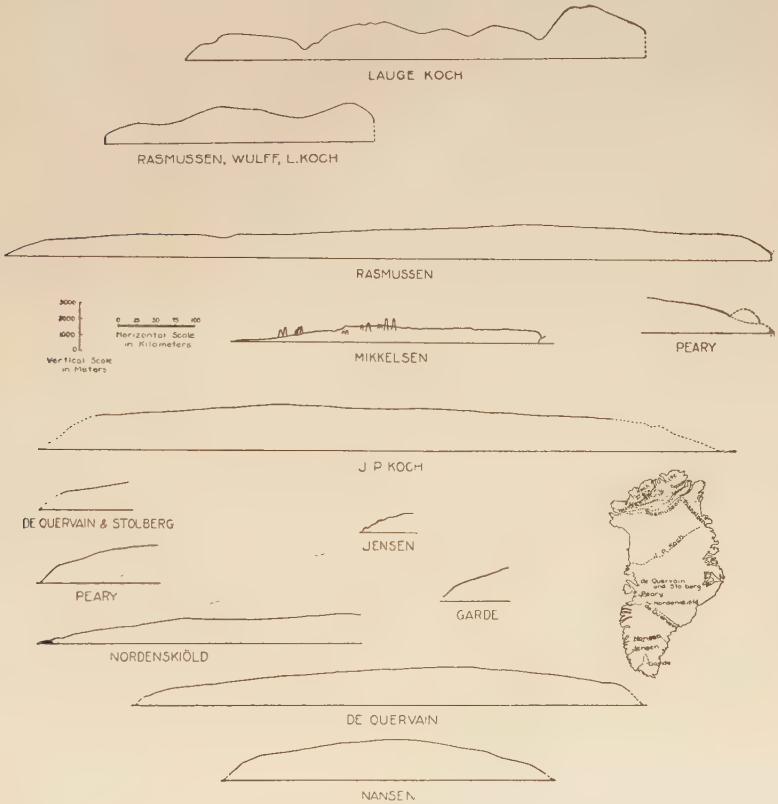


Fig. 39. Profiles derived from transections of the inland-ice of Greenland. All but the upper two are reduced to a common scale

[9] L. Koch, "Some New Features in the Physiography and Geology of Greenland," *Journ. Geol.*, vol. 31, 1923, pp. 42–65, 8 figs. Also, "Note to Maps of Melville Bay from Wilcox Point to Cape York and of North Greenland from 81°–83° 35′ N., 38°–56° W.," *Med. om Grönl.*, vol. 64, 1922, pp. 77–88, map; "Preliminary Report on the Results of the Danish Bicentenary Expedition to North Greenland," *Geogr. Journ.*, vol. 62, 1923, pp. 103–117, map.

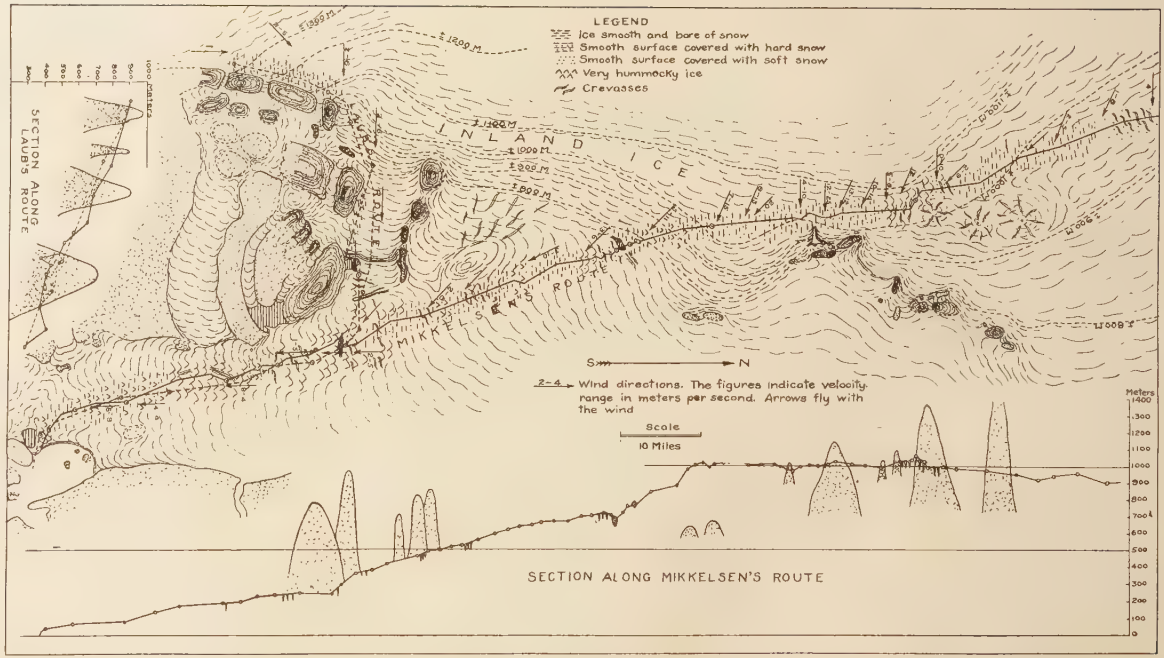


FIG. 40. Map and profiles of a part of Mikkelsen's sledge-journey across the inland-ice of northeast Greenland with the force and direction of the wind at each point of observation plotted from his records (amplified from Mikkelsen)

Mikkelsen's report on the Alabama expedition to northeast Greenland. — Mikkelsen in crossing the inland-ice of northeastern Greenland (Crown Prince Frederick VIII Land) in a general northerly direction, mapped his course with exceptional precision and was able to prepare a rough contour map for the area near his route. To the direction and the force of the wind, and to the nature of the surface of the glacier he also paid especial attention. By combining the data supplied by his tabular record of wind observations with his map and profile, as has been done in Figure 40, these results make one of the most instructive maps that have ever been prepared from a continental glacier. Nothing could be better for an exposition of the relation of the surface wind to the snow-ice slope.

De Quervain and Mercanton's final report on the Swiss Greenland expedition. — This report is illustrated by a profile and a map of surface contours of the glacier along the route followed. These are reproduced in the lower portion of Figure 41 and to them have been added the daily range of air temperatures measured along the route and reproduced for the first time in the narrative account of the expedition (see p. 66), but here first placed in correlation with the profile.

The general correspondence of the regions of moderate radiation characteristic of the slopes of the inland-ice with the areas of strong down-slope winds and storms will be at once apparent from examination of these sections. The marked spreading out of the contours of the map for the central section should also be noted. The sharp boundaries delimiting the diurnal ranges of temperature of the central from the slope sections are most striking, and they doubtless indicate both that radiation is much greater within the central section, and that the air being there more quiet and hence longer in contact with the colder snow surface has its temperatures approach more closely to that of the snow beneath. It is here, then, that the anticyclones are

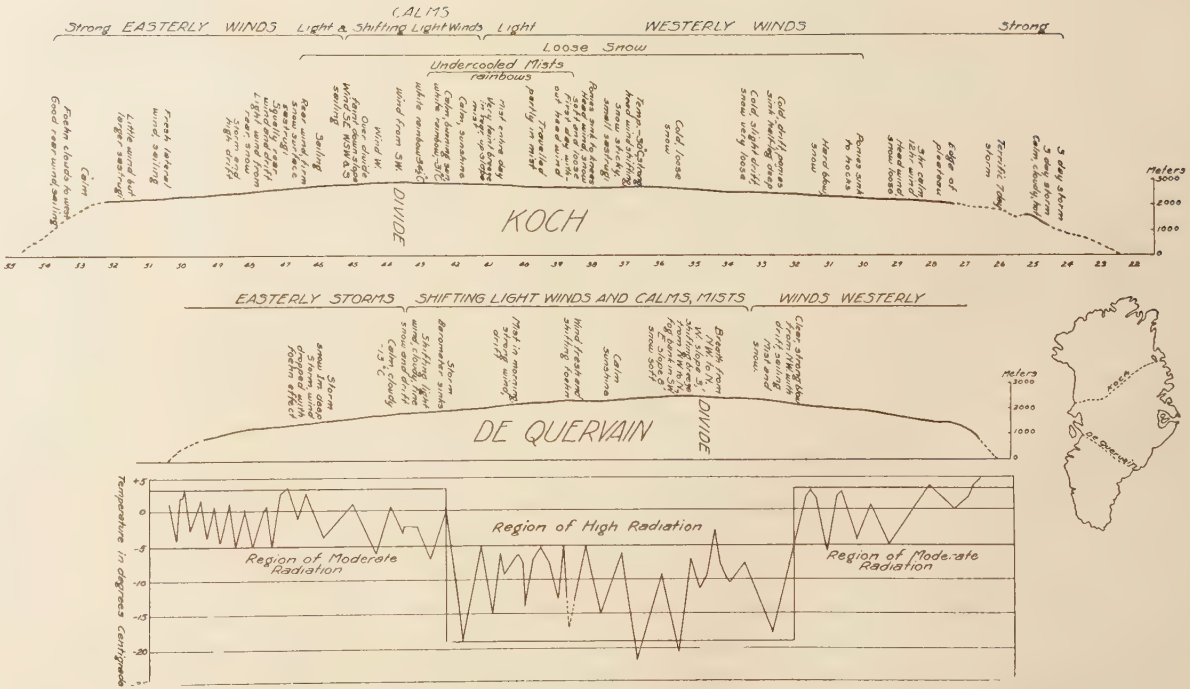


FIG. 41. Profiles of the sledge-journeys of J. P. Koch and of De Quervain across Greenland. The upper section from Koch's narrative is only approximate. To the lower profile and map after De Quervain and to the upper profile from Koch have been added important data derived from the narrative accounts.

chiefly generated. Confirmation of this is found in the general conclusions of De Quervain concerning down-slope winds and in the calms with shifting winds and mists within the interior region, which has been brought out in a general way in the preliminary narrative account. Speaking of his diagram showing daily air temperatures, De Quervain says:

> This central cold region is very strikingly set off from the marginal zones. In the first 13 days of the advance and corresponding to an increase of altitude from 550 m. to about 1900 m., the mean value of the temperature amounted to —0°85 from which the individual daily means ranged only 1–2°; a progressive fall is scarcely indicated. On July 3rd at 1936 m. we entered at once into a cold region that in time stretched out for 13 days and in space over the maximum elevation (2500 m.) until the elevation of 2250 m. was reached on the descent. Within this cold region the daily mean of the temperature amounted to — 10°.0 and ranged on the average not more than — 1°.6 from it; they attained as a minimum the daily mean of — 14°.1. Most abruptly, then, in the last five days of the transection, beginning in 2250 m., the temperature went up and amounted in the mean for this time to — 0°.02 (mean of the first day of this period — 0°.13).[10]

In this report De Quervain also brings out clearly the relationship of the down-slope winds to the general anticyclonic circulation. He says:

> According to the experiences on the crossing and from our knowledge of the distribution of air pressure at the time, we were compelled to remain under the impression, which any worker must gain from our meteorological tables, that the most strongly marked, highly regular connection exists between the summer wind conditions of the central Greenland inland-ice and its topography. On the west side of the gigantic ice-shield regular *southeast* winds varying from strong to tempestuous; on the east slope, likewise, somewhat less strongly marked *northwest* winds. Strongly stated, it appears indeed as if the air was streaming out after the manner of a liquid from the interior down the inclined slopes toward both coasts, but turned 45° to the right through the action of earth rotation.
>
> Such a determination, even for summer conditions, gives support to the assumption of very marked *inland-ice anticyclones* in the sense of the interesting demonstrations of W. Hobbs [in *Existing Glaciers*]. Our advance results have therefore given added value to these views.[11]

[10] *Op. cit.*, p. 117.
[11] *Op. cit.*, p. 113.

The foehn character of the down-slope winds is dwelt upon and cases of "total-foehn" and "double-foehn" discussed, always as a property belonging to the inland-ice anticyclone. Referring to the latter, the authors say:

> This case, in which the wind flows off as southeast on the west side, as northwest on the east side, can now, as already shown, be considered as characteristic, that it above all has to do with the outflow of the inland-ice anticyclone (p. 115).

Speaking of the atmospheric depressions, which Nansen considered in one or two instances to have sprung over the southern narrower portion of the inland-ice during his transection of it, and of Vincent's maps upon which tracks of depressions are shown crossing the inland-ice with the greatest freedom, the authors say that "of all minima which during the transection have appeared on the west coast of Greenland,[12] not one has, according to our observations, crossed over from west to east either in the latitude in which we were or to the north of it" (p. 115).

Concerning the moisture content of the air within the central region penetrated by De Quervain, the report is most illuminating:

> There is found, then, an average *decidedly high relative humidity*, 82% indeed for the whole, as for the central region, and a decidedly small daily range of relative humidity; this varies as an average of all days between the values of 88% and 77%; for the central zone the variation is somewhat greater, namely, between 92% and 73%. On the ice border the relative humidity is smaller by about 5%.[13]

During the entire crossing the directions of motion of the highest clouds (Ci, CiStr, CiCu) were seen to be from the northeast or the southeast quadrants (see p. 107). Once only (on the

[12] A meteorological station at which systematic observations were continuously made was established by De Quervain at the west terminus of his section.

[13] *Op. cit.*, p. 136.

west coast) cirri coming from the west were observed, and once on the east coast when an atmospheric depression lay about Iceland.[14]

The annual accretion of snow to the inland-ice was carefully measured along the route and has significance in reference to the shaping and to the question of manner of growth of the continental glacier, but the author appears to have overlooked the importance of the distribution of drift-snow as it relates to this question. He says:

> The mean for the west coast figures is 36.2 cm., that for the east coast 33.6. In the series of measurements for the west coast one finds an indication of increase of precipitation with height, in that of the east coast a decrease.

In view of the recurring periods of removal of the snow which lies upon the ground, series of determinations of this sort must vary greatly according to whether they were measured before or after a particularly heavy stroke of the anticyclonic broom.

De Quervain and Jost's "zone of subpolar whirls." — In relation to the traditional view of a circumpolar whirl which has been designated also "circumpolar cyclone," De Quervain and Jost,[15] after referring especially to the well-known view of Hann, have this to say:

> Thus it is without doubt to be understood when J. v. Hann in his treatise [3rd ed., p. 831] gives his opinion after a preliminary review of our results, that the insertion of these observations into the conceptions which have been held up to this time is not easy; for the reason that one should expect west winds — even the polar whirl.
>
> In order to maintain with right a distribution of air pressure within the higher layers which would be in harmony with our observations, it would be necessary to regard the low surface temperatures of the north Greenland anticyclone as entirely local and shallow, and to push upward the source of the excess of pressure within the upper layers and look

[14] *Op. cit.*, p. 144.

[15] "Aerologische Arbeiten Sommer 1912 und Ueberwinterung 1912–13," *ibid.*, pp. 309–402.

upon them as dynamic. The body of this anticyclone should then up to the great altitudes be no colder than is the air above the low pressure area lying over Davis Strait and Baffins Bay.

This anticyclone gains in interest when it is placed parallel to that which is postulated around the South Pole and confirmed by the east winds. This antarctic anticyclone is assumed by Meinardus to be shallow and to be overblown in great heights by west winds which have a rising component and constitute a superimposed polar whirl, which can bring the necessary precipitation for the nourishment of the inland-ice — whereas Hobbs, indeed, has endeavored to prove the possibility of the nourishment by purely anticyclonic conditions.

However that may be, the impression of the qualitative equivalence of these two anticyclones is compelling, of which the Greenlandic one by reason of its excentric position with reference to the pole proves a relationship not so much to the latitude as to the form of the inland-ice.

Our conception of the problem of the building up of the inland-ice comes into contact with (*berührt*) that which, based in fact upon our results of 1909 and 1912–13, has already been developed by W. J. Hobbs in 1910 and 1915 (most recently in Proc. Am. Philos, Soc., vol. 54, no. 218, Aug., 1915). As regards the polar whirl, with reference to the investigations of Barkow in the Antarctic and to our results of 1909 and in part 1912, he comes to the far-reaching conclusion (p. 215): "It seems that the time has arrived for laying the specter of the circumpolar whirl, and of returning to an objective basis of reasoning."

That the conception of a more or less individual Arctic polar whirl, which should exist at least within the higher strata, in part as a consequence of our observations, is shown to be too schematic, is hardly to be denied; near the other extended land masses, particularly the continent of Greenland domed over by plateau-ice and with its anticyclone, it is forced off to the southward beyond the polar circle and tends to be broken up (*sprengen*). The fact of the mighty girdle of prevailing westerly winds of moderate latitudes extending up the great heights, even if they represent the average of individual wandering whirls, still continues to endure, to the empirical data of which Hildebrandsson has recently drawn our attention. This important part of the wind system of the earth one must now designate, moreover, by a significant name which shall point to the indispensable conception of a general circulation; having reference to its removal from the pole and to its breaking up into individual vortices one would now speak with greater aptness of a *zone of subpolar whirls,* instead of a "polar whirl."[16]

It is very much to be hoped that this most inapt expression, "zone of subpolar whirls," will not be adopted, and this for the following reasons among others:

[16] *Op. cit.,* pp. 375–376. The German of these authors is exceedingly difficult to translate.

1. It is by its terms, as by the introduction to it by its sponsors, a confessed attempt in the interest of a great man of science to bolster up a speculation which he had fought in vain to defend and which is now shown to be untenable. As we have shown, Professor Hann first fought vigorously for the "circumpolar cyclone" against the evidence for an anticyclone which for the Antarctic region had been brought forward by Bernacchi; and by his great influence he was able to give a wrong slant to all the meteorological interpretations by the earlier British workers within the Antarctic. When Scott on his first expedition had encountered west winds upon the inland-ice of South Victoria Land and recognized them as slope-winds, these were by Meinardus seized upon as indications of a cyclone above the clearly indicated anticyclone, and Hann with great vigor defended this view. When now in turn the observations of Barkow and of De Quervain and Jost show that no cyclone whatever exists above the anticyclone, these authors now urge that something quite different in its nature and in a different zone of the earth, be twisted into a modified form of the expression, "circumpolar whirl," the effect of which must be to cause further misinterpretation and tend to gloss over the stupendous error which has been made and stubbornly defended in the face of ever increasing evidence to refute it.

2. The "zone of subpolar whirls" is neither subpolar nor composed of whirls of the kind which the early form of the expression is intended to indicate. It is not even a zone in the climatic sense. The whirls which are referred to are a continuous procession of migrating cyclones and anticyclones in alternation, and for the most part they are within moderate, not subpolar, latitudes; whereas the conception of the polar whirl was not a zone at all, but a vortex essentially fixed in position and centered over the pole.

3. The adjective "subpolar" ignores the one dominating

conclusion which has been reached as a result of all Greenlandic studies, including particularly those of De Quervain and his associates; and this conclusion is that we have here to do not with a system of air circulation disposed with reference to the pole at all, but dependent upon a high domed mass of cold snow and ice centered nineteen degrees of latitude from it.

The proposed expression tends then to perpetuate the traditional error on the part of meteorologists generally, that questions of air circulation must all be referred to latitude rather than to other dominating conditions.[17] It ignores the fact that the two polar regions are quite in contrast because the world's two vast anticyclones are in the one case centered nearly over the geographical pole, and in the other in a highly eccentric position. The tendency to correlate observed altitudes of the ceiling of the troposphere with regard to latitude, is one example only of this strong tendency. The probability is very great that the lowest area in this ceiling within the northern hemisphere, instead of being over the North Pole, is centered over the anticyclone of Greenland.

J. P. Koch's narrative report. — It is much to be regretted that the final report upon an expedition completed in 1913 should have been so long delayed. This distinguished explorer has, however, fairly crammed his narrative report with essential scientific facts, and these are fraught with such importance in relation to the problem of the anticyclone and bear such close correspondence with those obtained by De Quervain and others, that at considerable pains they have here been extracted and are presented upon the profile of Figure 41, where they appear beside those of De Quervain.[18] We find here the same differen-

[17] Seldom more strikingly illustrated than by the presidential address of Dr. Simpson, head of the Meteorologic Office, before Section A of the British Association on Aug. 28, 1925.

[18] The profile while based on astronomically determined positions and upon elevations given in the report, is nevertheless not to be regarded as

tiation of slope and interior regions which has been elsewhere determined, with much the same meteorological characteristics within each. The undercooled mists encountered by Koch recall those which were first observed by Baron Nordenskiöld in 1884 in southwest Greenland (see p. 80). Foehn conditions were pronounced and characteristic over Queen Louise Land, where the winter quarters were located, and the pronounced foehn clouds which were seen from a great distance over the inland-ice, brought the first hopeful augury that, as they must be above the western margin to the inland-ice, the end of the long journey was already in sight.[19]

Shackleton's skirting of his newly-discovered Caird Coast in the Antarctic. — This cruise by Shackleton has supplied certain additional scientific data relating to the Antarctic glacial anticyclone. The available observations have here been taken from his narrative account [20] and from a preliminary notice on the meteorological data prepared by Mossman.[21]

All the data which concern wind directions encountered near the inland-ice along the southeastward shore of the Weddell Sea (Bruce, Filchner and Shackleton) have here been combined in one map and reproduced in Figure 42. It will be noted that Shackleton on his cruise skirted Coats and Caird coasts and the termination of Luitpold Coast. The winds are seen to be uniformly off-shore down-slope winds deflected by earth rotation,

---

strictly correct; since the explorer discovered errors in his longitudes before the west coast had been reached. The western slope is, therefore, probably too steep, and the crest located too far to the west. Nevertheless the profile is sufficiently correct for the broad interpretation of the data which have here been entered upon it.

[19] *Op. cit.*, p. 140.

[20] Sir Ernest Shackleton, *South,* Macmillan, 1920, Chapter II.

[21] R. C. Mossman, "Meteorological Results of the Shackleton Antarctic Expedition 1914–1917 (Weddell Sea Party): Preliminary Notice," *Quart. Journ. Roy. Meteorol. Soc.,* London, vol. 47, 1921, No. 197, pp. 65–70.

and the same is indicated for Luitpold Coast farther to the southwest on the basis of Filchner's data.[22]

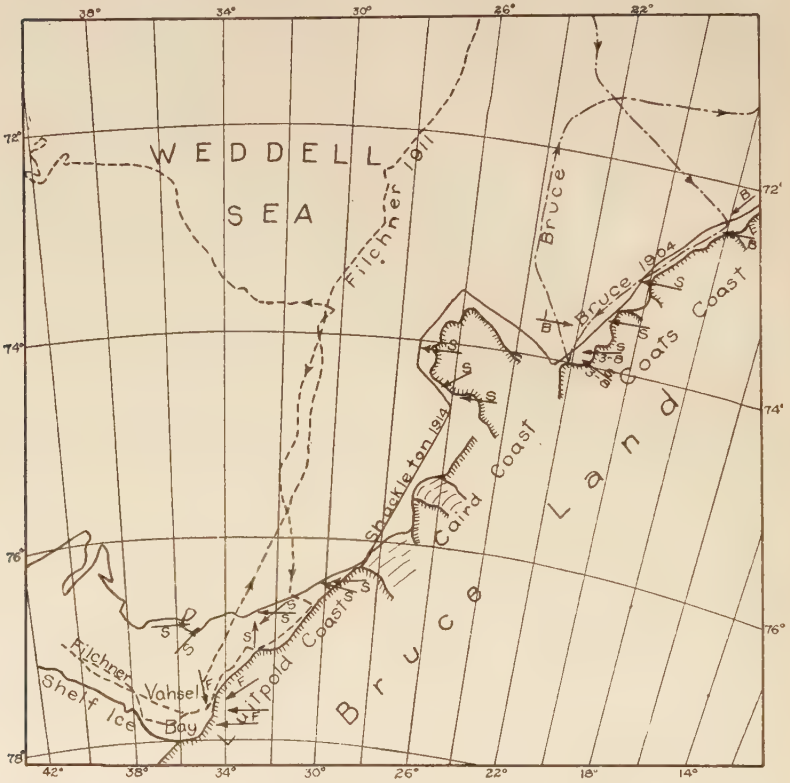


FIG. 42. Sketch map of Bruce Land and the neighboring portions of Weddell Sea showing wind observations (based on maps by Bruce, Filchner and Shackleton, to which have been added wind observations from their various reports)

Simpson's final report on the meteorology of the Last Scott Expedition. — The final report of Simpson, the meteorologist of the Last Scott Expedition to the Antarctic, comprises three

[22] See Przybyllok, *op. cit.*

quarto volumes.[23] His discussion of his observations upon the upper-cloud directions observed at Cape Evans and Cape Adare have here already been considered in connection with a review of his preliminary report (see p. 102). He now supplies, however, extremely interesting roses for the cirrus clouds and for the surface winds (Fig. 43).

Simpson's discussion of "The General Air Circulation over the Antarctic" comprises Chapter VII of Volume I (pp. 249–269). Inasmuch as he has failed to grasp the idea of the relationship of the Antarctic winds to Antarctic topography, and for this reason has misinterpreted my statements, it is necessary to cite his paragraphs somewhat fully. After quoting Lockyer and Hepworth and apparently upon this basis accepting an anticyclone over the "Antarctic region" as established, Simpson says:

> Hobbs goes still further and contends that an anticyclone exists over every extensive snow-covered land and takes the Antarctic and Greenland as the two most pronounced examples. To the anticyclones which owe their origin to a snow-covered land Hobbs has given the name "glacial anticyclone" and he has worked out at considerable length the meteorological features of such anticyclones. His conclusions as to the conditions over the Antarctic are so important that they must be considered in detail here. . . .
>
> On considering the whole of Hobbs's paper one cannot help feeling that in spite of his failing to explain the origin of the precipitation and the mechanism of blizzards he has made out a very strong case for the existence of an anticyclone over all extensive masses of inland-ice and over the Antarctic in particular. . . .
>
> Thus the theories of Hobbs and Meinardus are totally opposed, the latter deducing that the greater part of the Antarctic is subject to a cyclonic pressure distribution while the former declares that over the whole Antarctic there is a strong anticyclone.[24]

This is of course in part quite contrary to what I have from the first contended; namely, that the domed ice-surface, not the

[23] G. C. Simpson, D. Sc., F. R. S., *British Antarctic Expedition 1910–1913*, vol. 1, Calcutta, 1919, *Discussion;* vol. 2, Calcutta, 1919, *Weather Maps;* vol. 3, London, 1923, *Tables.*

[24] *Op. cit.*, pp. 248, 251, 256.

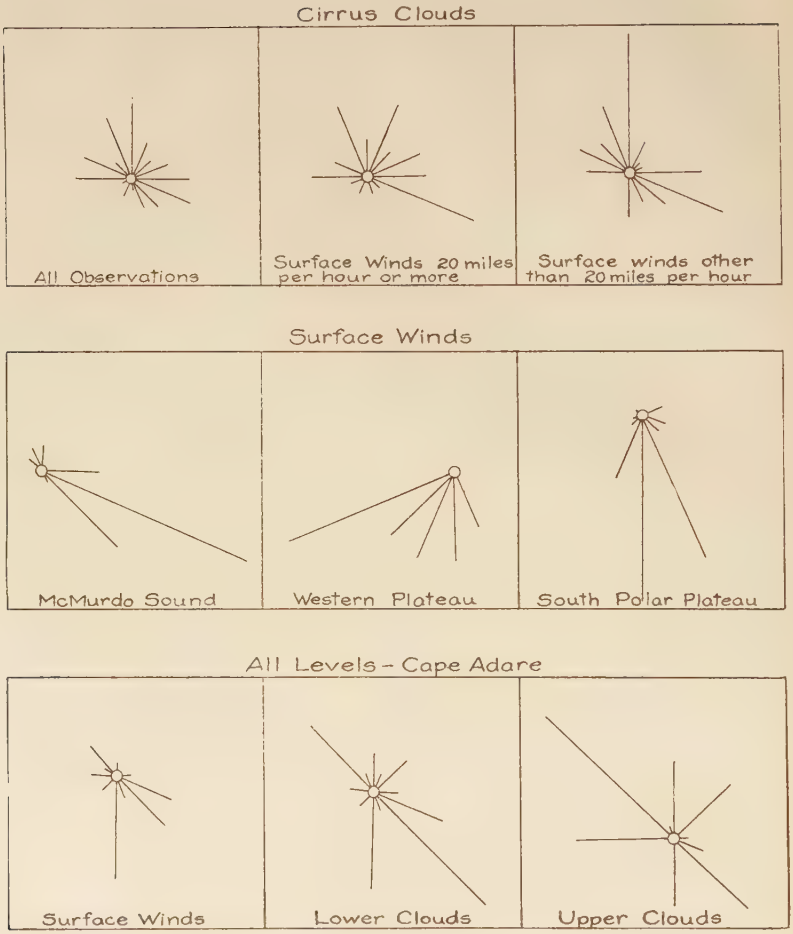


FIG. 43. Top diagram, mean roses for cirrus cloud directions observed at Cape Evans. Middle diagram, mean roses of surface winds observed at British station on McMurdo Sound and on the western and southern plateaus. Bottom diagram, wind roses for the surface winds, lower clouds, and upper clouds observed at Cape Adare (after Simpson)

snow-covered land, is the direct cause of the anticyclone. Moreover, the origin of the precipitation and the mechanics of the blizzards, contrary to Simpson's assertion, are fully accounted for; but he fails to take account in his studies of that moisture which is locked up in ice-particles until it is made available as moisture through an adiabatic transformation. This misreading of my monograph has been commented upon by Dr. Hugh Robert Mill, the veteran meteorologist, long the director of the British Rainfall Office, and an eminent authority on the Antarctic, and I have made reply to Simpson in a special paper.[25] Mill comments as follows: [26]

> Dr. Simpson accepts with approval the theory of the glacial anticyclone put forward by Prof. W. H. Hobbs, of Ann Arbor, though, no doubt by an oversight, without attaching sufficient weight to Professor Hobbs's fundamental contention that an anticyclonic circulation is only set up completely when the cold surface has a dome-shaped contour.

Inasmuch as it has proved difficult for some meteorologists to grasp the significance of the rôle of the domed-surface of the glacier in producing the mighty vortex of the glacial anticyclone, two small pieces of apparatus were at this stage devised for the purpose of demonstrating in part experimentally this circulation (see Plates II and III).[27] For lecture purposes where it is necessary to demonstrate the principle optically to a considerable number of people, the device shown in Plate II is employed. Here water at room temperature is contained in a glass tank at the bottom of which is placed either a hollow dome or the section of a hollow cylinder of copper into which ice water can be quickly introduced. Crystals of a strong coloring substance, for example, Victoria green, are placed upon the screen at the bottom of a container inserted in the water above

[25] *Proc. Am. Phil. Soc.*, vol. 60, 1921, pp. 34–42.

[26] *Geogr. Journ.*, vol. 56, 1920, pp. 213–216.

[27] W. H. Hobbs, "The Mechanics of the Glacial Anticyclone Illustrated by Experiment," *Nature*, London, July 22, 1920.

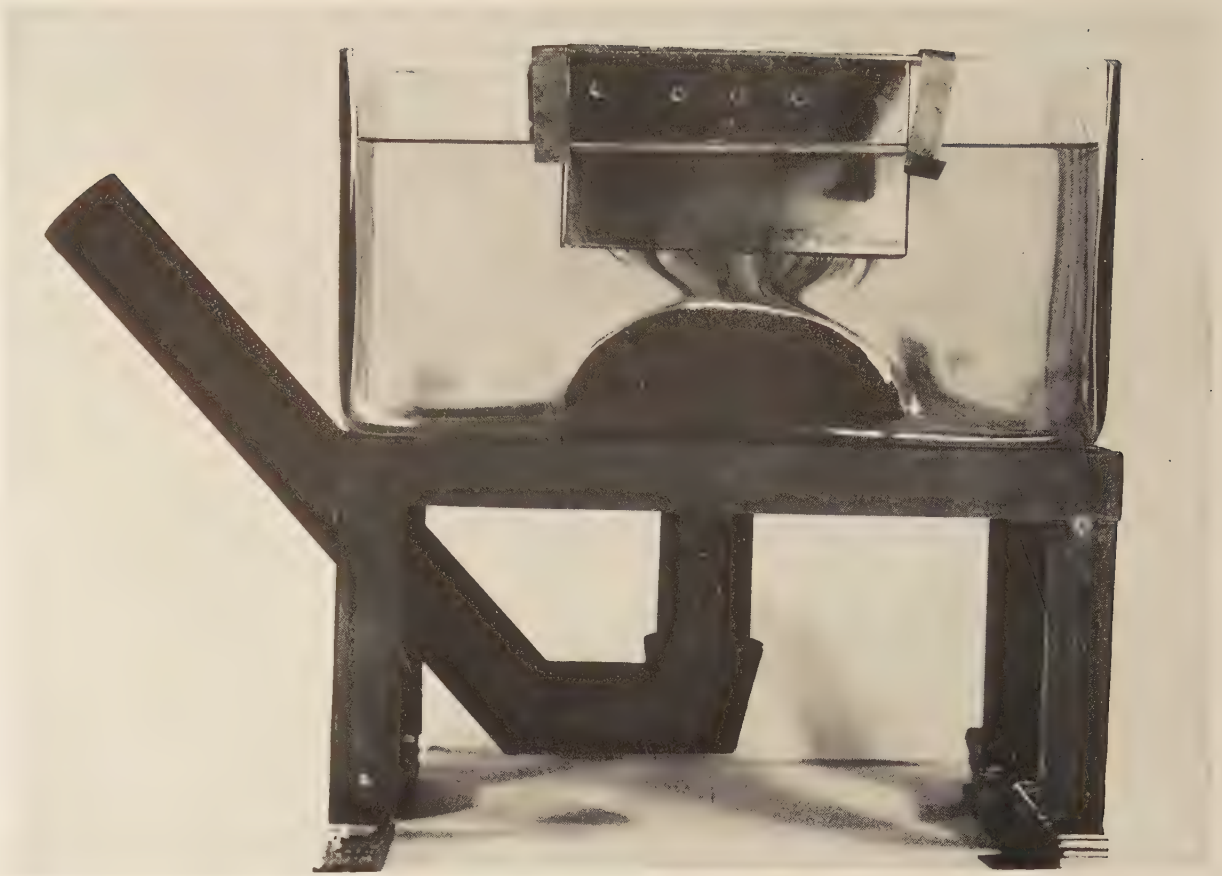
the dome. So soon as the copper dome is cooled by the ice water poured into it, cooled surface currents stream off its slopes within the tank, drawing down in a vortex the water from above which has become strongly colored and which brings out with great distinctness the form of the anticyclonic vortex as an hour-glass shape as well as the spirally-directed currents within it. Although this miniature anticyclone is generated with the greatest ease, its arrest and the whole mechanism of the blizzards, involving as these do adiabatic changes due to great change of altitude, could obviously be brought about only upon the scale of the glacial anticyclone itself.

To demonstrate the glacial anticyclone to a few individuals only, air itself, instead of water, can be employed as the circulating medium within the simple device which is shown in Plate III. Here a lighted cigarette is employed or, much better, a minute cup filled with ammonia set in a watch glass containing concentrated hydrochloric acid. The latter yields the white fumes of ammonium chloride which are seen with great distinctness. Almost immediately upon introduction of the ice water into the copper dome (and this can best be done, it has been found, by filling the dome and placing it gently in the jar), the smoke or the fumes, as the case may be, stream down the slopes of the dome taking the form of an hour-glass with helical elements marking its contours.

Simpson's own conception of the air circulation "over the Antarctic" he has summarized in the following paragraphs: [28]

> A statement of the general air circulation over the Antarctic is now quite simple. Over the snow-covered surface of the Antarctic, whether at sea-level or at the height of the plateau radiation is so strong that the air is abnormally cooled especially in the layers of air immediately above the surface. This cooled air is heavier than the surrounding air and therefore the pressure increases from the exterior to the interior of the Polar area; in other words the pressure distribution is anticyclonic and the air motion is in general outwards. Above each anticyclone a cyclone forms

[28] *Op. cit.*, pp. 268–269.



Device to Show an Artificial Glacial Anticyclone Produced in Water

PLATE III

Device to Show an Artificial Glacial Anticyclone Produced in Air

on account of the relatively rapid vertical pressure change caused by the cold dense air. These cyclones convey air from higher [lower?] latitudes over the Polar region and supply the air which passes outwards near the surface. In the normal steady state the air circulation takes place slowly and the descending air is warmed up dynamically so dissolving cloud and giving clear cloudless skies, thus accounting for the decreasing cloud amounts observed as one penetrates the Antarctic.

The clear skies in their turn facilitate radiation as also does the small absolute humidity of the air. In consequence the air and the snow surface become abnormally cold and there is a great tendency to the formation of temperature inversion especially in the lower atmosphere. On these normal fine weather conditions are superposed a series of pressure waves which travel more or less radially outwards from the centre of the continent. These waves alter the surface pressure distribution and cause air motion which is frequently, and especially over the west of the Barrier accompanied by forced ascending currents. The abnormally cold surface air is forced upwards in these currents, rapidly cooled in the ascent, and the water contained is precipitated as snow, which when combined with the high surface winds produces the typical Antarctic blizzard.

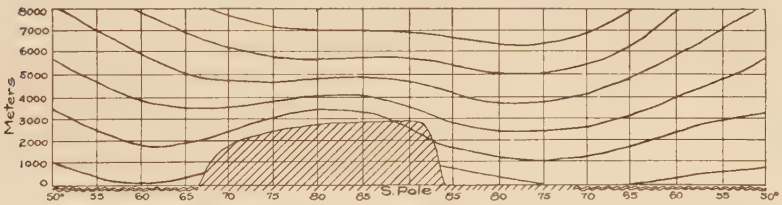


FIG. 44. Probable distribution of Antarctic air pressure in vertical cross-section according to Simpson's conception (after Simpson)

In common with many meteorologists Simpson in his equating of the moisture content of bodies of air, considers that water only which can be indicated by a hygrometer, that which is present as vapor.[29] He quite overlooks the fact that in the strong adiabatic changes which go on in the anticyclone the ice particles characteristic of the high-level clouds, which in fact permit them to be seen and which have been seen at close hand by men in balloons, must also be taken into account if the meteorological equation is to balance.[30] Simpson says:

[29] Cf. A. Wegener, "Über Temperatur inversionen," *Beitr. z. Physik. d. frei. Atmosphaere,* vol. 4, 1910, pp. 62–63.

[30] It should be noted as a fact of the utmost importance that the

Thus Hobbs appears to be right in his main contention that the surface of the land both high and low is subject to anticyclonic conditions, but we are still faced with Meinardus's main contention, that under such conditions evaporation will exceed precipitation and the Antarctic should be denuded of its permanent snow-covering.[31]

It seems necessary to repeat to some extent what has already been said concerning the conditions within the interior areas above inland-ice domes (see p. 80), and a further word should here be said concerning the mechanism of the inland-ice blizzard. Of my explanation of the blizzard Simpson says:

According to it the blizzard is the result of the cooling of the lower air layers which is supposed to proceed until the dense cold air over the inland-ice becomes unstable when there is a great outrush of cold air towards the surrounding warm air over the ocean. . . .

It would be interesting to know what has been holding the heavy air in place. . . . All theories similar to this neglect the fact that the air will start to move as soon as it commences to cool. . . . (pp. 250–251)

Quite true, it will start, but like all bodies sliding out on inclined planes of flat gradient, it will start with extreme slowness and acquire velocity to accord with the law of acceleration of gravity. It is necessary to say that once more we have here to do with a very careless reading, and that the foregoing statements all do violence to my views. I shall, therefore, take the space here to put in clearer light, if possible, the process as I have conceived it by which the blizzard is first started and finally terminated. The characteristic weather over all observed areas of inland-ice, with possible exception of that of Adelie Land studied by Mawson, consists of an alternation of calm

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assumption of Simpson on which he restricts the extent of the Antarctic Continent to one side only of a line which would join the west side of Ross Sea to the east side of Weddell Sea, is entirely gratuitous and not in harmony with the views of most Antarctic explorers. As a matter of fact, the inland-ice of the Caird and Luitpold coasts and that reached by Nordenskjöld in King Oscar II Land, like that of King Edward Land, are all located well out in this area indicated to be near sea-level and covered by low atmospheric pressure.

[31] *Op. cit.*, p. 265.

with blizzard. We have learned how excessive radiation from the *glacier surface within the interior* and consequent absorption of heat from the surface air layers, starts the movement of air outward, *but on an almost horizontal surface.* The movement is therefore slow at first, but gains velocity gradually. Corresponding to this movement outward to displace warmer air on the slopes, the column of air above the central area of the anticyclone begins to move downward and to spill out in every direction at the bottom. The ice-particles of the cirri high up in this column as they descend are first melted and later vaporized by the adiabatic elevation of the temperature, in connection with which there must occur an abstraction of heat from the air and a transformation of energy which brings about a lag in the progress of the evolving anticyclonic movement.

When the velocity of outward down-streaming has arrived at full blizzard proportions on the slopes of the dome, the measure of the adiabatic elevation of temperature for the first time becomes an important factor in the process. Though abstraction of heat from the air is a direct function of time, adiabatic elevation of its temperature is a direct function, not of time, but of the vertical component of the velocity. With high wind velocities, the considerable elevation of temperature comes about suddenly and more than offsets the effect of the surface cooling. Since the outward movement of the air is in consequence suddenly arrested, there follows a calm and even a slight reverse movement — the anticyclone may momentarily turn itself inside out and become for a brief interval a weak cyclone. Observations show that some fresh snow is precipitated as the blizzard comes to an end, and latent heat thus made suddenly sensible, the elevation of air temperature due to the rapid descent of the air is still further augmented.

Within the interior region, however, because of the heavy radiation and absorption of heat, the vaporized moisture from

the ice-particles of the cirri appears to be almost constantly crystallizing out and being deposited upon the surface. The observations of Peary, Amundsen, Scott, J. P. Koch, and De Quervain — all who could offer direct testimony — are harmonious upon this point.

The self-registering balloon ascents which were carried out by Simpson near the British winter quarters were extended in winter up to an altitude of 2500 meters, and in summer to the height of 6500 meters. The summer temperature curve is quite striking for its rectilinearity, lacking wholly the evidence of a lower inversion, but as already pointed out, the station was so remote from the inland-ice that the winter anticyclones only controlled it directly. The winter curve shows a most striking inversion within the lower 1000 meters. Such a lower inversion, as is shown above, has been observed on both coasts of Greenland, particularly where the warm foehn winds from the plateau slide out over more slowly moving and cooler surface layers (Fig. 45) and we shall see that it has also been found on the borders of the inland-ice of the Luitpold Coast, Antarctic (see Chapter IX).

Wright and Priestley's report on the glaciology of the last Scott expedition. — In the report of these observers the importance of the ice-dome as a cause of the anticyclonic circulation is somewhat more clearly recognized, and a clearer conception of the manner of precipitation of snow as above described is seen. This is thought by them, however, to have less importance than certain other considerations. These authors say: [32]

> Professor Hobbs explains the wind circulation of the Antarctic Continent and of Greenland as the result of the cooling of the surface air by contact with the cold elevated snow-covering of the Plateau, the cold air then streaming down along the line of greatest slope at each point. He has also proved experimentally that a small cooled dome-shaped surface will indeed cause such a circulation. Such an explanation is adequate to account for the observed air circulation during the winter, but if Hobbs'

[32] *Op. cit.*, pp. 9, 177.

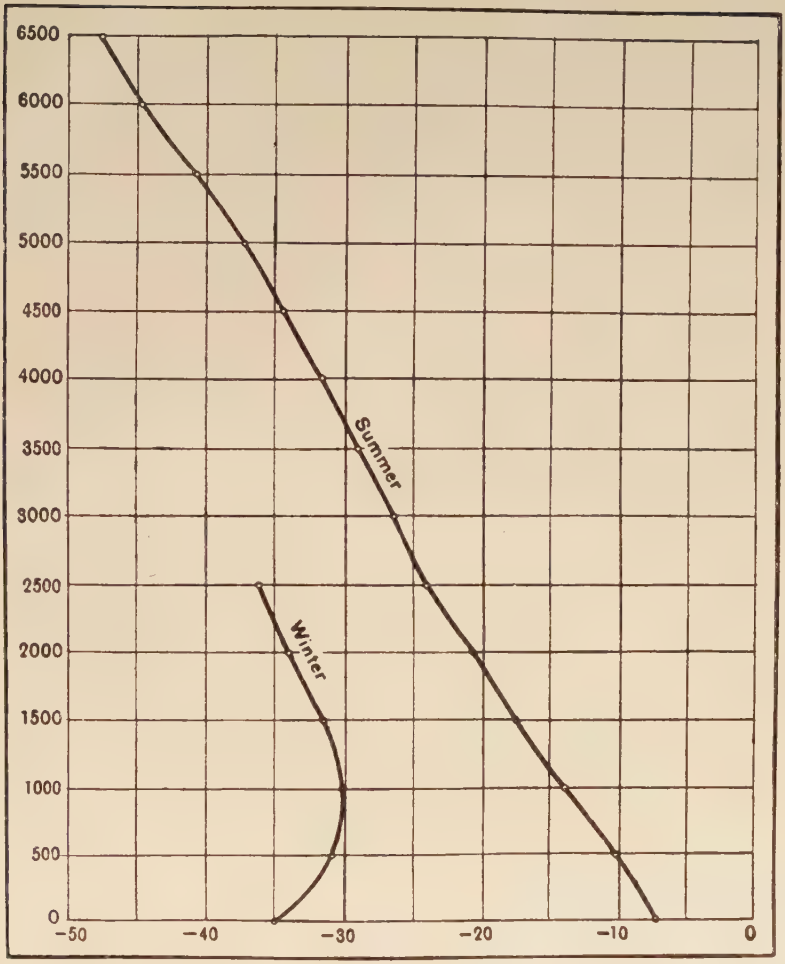

FIG. 45. Temperature curves for the upper air based on balloon ascents near British winter quarters at Cape Evans (after Simpson)

explanation is correct, it is not easy to see how the snow surface can cool the air in contact with it *during the summer* . . . when radiation from the sun is comparatively intense. It may also be pointed out that in December and January, the wind blows definitely uphill in the neighborhood of the South Pole.

I believe the fact that nearly all observations over inland-ice have been taken in the summer, including the study of snow temperatures beneath the surface in the interior carried out by J. P. Koch (see p. 79), answers sufficiently one of the points raised by Wright. My reading of the accounts by both Amundsen and Scott when in the neighborhood of the South Pole, is that they encountered shifting light winds, but no strong winds and no sastrugi were observed. It is of course true that Scott and Amundsen were descending slightly as they approached the Pole.

Wright continues:

> Objections to Hobbs' view, that a glacial anticyclone lies everywhere above the Continent, have been raised, on the grounds that an anticyclonic pressure distribution demands an excess of evaporation over precipitation; whereas it is known that immense masses of ice are yearly discharged into the sea in the form of icebergs, so that precipitation must, in fact, exceed evaporation.
>
> As pointed out by Dr. Simpson, precipitation of snow can take place on the surface in the manner postulated by Hobbs, and there seems no doubt that precipitation of this type does occur in the Antarctic. The amount is, however, small, and greater snowfalls would occur if air close to the ground were, in any manner, forced to move faster than that in front of it. Such an action would cause the air behind to rise and precipitate a portion of its moisture in the form of snow. As will be seen later, the pressure distribution accompanying blizzards provides the mechanism for such a movement. It must be emphasized, however, that the factor predisposing to snowfall which operates most strongly in winter is powerful radiation from the snow surfaces.
>
> . . . It frequently happens that the cold layer found near the surface at first allows the faster moving layers of air to slide over it, the blizzard only extending down to the earth's surface when this protecting layer has been swept away. . . . (p. 9.)
>
> As regards the continuance of the glacial anticyclone in summer, we would suggest that the dome-shaped surface may be the result, rather than the cause, of the glacial anticyclone. We would, in fact, prefer to place the origin of the anticyclonic conditions at the boundary between snow-covered continent and either open water, water with ice-covering, or bare rock surface. At such a line of demarcation a horizontal temperature gradient must exist.
>
> If this can be granted, as seems reasonable, the prime cause of the anticyclone is associated with the difference between the physical properties of a snow surface and the adjacent rock or water surface, one con-

tributory factor being the high reflectivity of the former. The descent of air in the center is a natural consequence. . . .

In these conditions, the descending air will probably be warmer than the ice surface and may deposit snow on contact. The cooled air will then flow generally downhill as in the manner postulated by Hobbs.

The essential difference between our view and that of Hobbs is, that a dome-shaped shield of Continental-Ice can, given a favorable climatic environment, arise on any glacierized land-mass, irrespective of the original contour of the ice surface. The glacial anticyclone is, therefore, not dependent upon a pre-existing dome surface, but upon the horizontal temperature gradient around the boundary of the glacierized region. *The dome-shaped contour is a result, and not a cause* (p. 11).

This appears to have to do with the inception of the ice-dome rather than with the cause of its great vigor today. Doubtless some horizontal temperature gradient would exist along the margin of a snow-covered area without glaciers with the sea or with bare rock; and an anticyclone would probably be set up such as apparently now exists during the winter season only over the great cold interior region of Siberia. This view is essentially that of Von Helmholtz which was first expressed in 1888 (see p. 20). Such anticyclone might by nourishment, partly at least of its own supplying, gradually build up an ice-dome or continental glacier. That this now fully-fledged and vast ice-dome, characterized as it is by strophic spasms surpassing in their violence even a tropical hurricane, can have much in common with its non-domed embryo, seems, to say the least, extremely improbable. That the present vigor of the glacial anticyclone is a consequence of its contour, even though some suggestion of its present mode of circulation may have characterized its humble beginnings, seems to be clearly indicated by the directions of the sastrugi in South Victoria Land (see Fig. 21, p. 57). *These sastrugi have directions which make the common margin of inland-ice and low, flat shelf-ice of the Ross Barrier; — the margin of the domed surface, not the margin of the shelf-ice and the sea or of sea-ice — the significant delimiting boundary.*

Priestley in discussing conditions at Cape Adare seems to have accepted the doctrine of the glacial anticyclone as accounting fully for climatic and meteorological conditions there.[33]

Barkow's posthumous final report on the meteorology of the Filchner expedition. — The extremely valuable preliminary report on the meteorology of this expedition was brought out by Barkow two years after his return, and this has already been treated (see p. 96). The World War which soon followed delayed the completion of the final report which was, however, ready in 1922. Before the means for its publication had been found, the author died in 1923. Edited by Dr. K. Knoch his monograph was issued in 1924.[34]

The value of this report lies particularly in the fact that it includes the results of the only upper air observations which have yet been made at any point close to the margin of the inland-ice of the Antarctic; those of Simpson in South Victoria Land having been made at too great a distance to have great significance. It will not be necessary to repeat here what has already been discussed in connection with Barkow's preliminary report, but I shall render in translation the more significant passages from the final summary chapter of the final report, which is entitled, "General Considerations on the Air Circulation in the Antarctic."

It should be stressed that these conclusions are based upon direct observations in the upper air made on and near the inland-ice of the Luitpold Coast of the Weddell Sea, Antarctic.

The streaming off of the air follows the slope of the inland-ice without being deflected essentially by earth rotation. The local gradient which

[33] R. E. Priestley, M.C., M.A. (Cantab.), *British (Terra Nova) Antarctic Expedition 1910–1913, Physiography* (Robertson Bay and Terra Nova Bay Regions), London, 1923, pp. 45–46.

[34] E. Barkow, "Die Ergebnisse der meteorologischen Beobachtungen der deutschen Antarktischen Expedition 1911–1912," herausgegeben von K. Knoch, Veröffentl. des Preusz. Meteorol. Instituts (v. Ficker), Nr. 325 Abh., Bd. VII, Nr. 6, Berlin, 1924, pp. 166.

determines the streaming off, always operates over but the smallest units of course. It is, so to speak, a differential gradient. The deviating force of earth rotation has had, so to speak, no time to operate. Only with slight slopes or with flat regions can earth rotation exercise an appreciable influence. Furthermore, the deviating power of earth rotation is small . . . and cannot properly come into existence against the fall of the cold masses of air, which indeed prove a hindrance. The wind velocity with this streaming off must always be proportionally large, since the movement follows directly the slope or makes a very small angle with it. . . .

From the foregoing considerations it follows that the streaming off of the air from the region of the inland-ice with existence of inversions, is at a maximum on the surface, and falls off with the altitude in order still higher up to be transformed into the opposite condition, an instreaming. The altitude of the layer of equilibrium we can estimate in round numbers as 1000 m. The outward streaming of the air from the interior of the Antarctic, as follows from the foregoing discussion, becomes so much the stronger the greater is the inversion. . . . The explanation of these winds off the land is, then, to be compared with that for the valley winds in mountain valleys. There is, however, a stupendous difference in the dimensions, since we are here concerned with the streaming off of the air from an entire continent.

Since the inversion in winter is in general greater, so the wind velocity on the border of the inland-ice must have a marked annual period with a maximum in winter and a minimum in summer. Further, the wind velocity must depend on the slope of the country. Since this slope is greatest in the neighborhood of the sea . . . so the wind velocity must be greatest within the marginal regions (p. 155).

How sharp the wind parting on the margin of the inland-ice itself may be, is shown by our direct observations in Vahsel Bay. On the inland-ice itself immediately at the border we had much more frequently winds off the land than upon the sea only a few kilometers distant (pp. 156–157).

As a general conclusion from what has been said it follows that the entire continent of the Antarctic is covered with an anticyclone,[35] whose actual thickness is of the order of magnitude of 1000 m. (p. 157).

The stationary lows in the Weddell and Ross Seas lie where they are, not because these indentations are occupied by the sea, but because they are at the level of the sea and therefore at a low level (p. 162).

With all these considerations I agree fundamentally with the Hobbs views (among others in the latest form in *Proc. Am. Phil. Soc.*, 1915, pp. 187–225), according to which an anticyclone controls the Antarctic region. . . . With this I place myself in opposition to the views of Meinardus. The latter advocates the view . . . that only the borders of the Antarctic are controlled by an anticyclone, whereas the interior because of its altitude pushes up into the overlying cyclone (p. 163).

[35] "Anticyclone" throughout Barkow's report clearly refers to the lower outstreaming portion of the vortex. The upper portion he describes as "cyclone." The definition of Meinardus is totally different.

Barkow appears to have been very doubtful about the origin of the snow which nourishes the Antarctic glacier, and his explanation, which is in part mathematical and which he put forward apparently with but little confidence, is somewhat difficult to understand. It will not be taken up here and the reader is referred to the original.

A very important series of observations was undertaken by Barkow to determine the comparative radiation from the surface of the inland-ice and from the sea, a line of research which is entirely new [36] and of the utmost significance in connection with the glacial anticyclone (see summary of Wright's views, p. 132).

When the *Deutschland* lay in the Vahsel Bay, a few kilometers only from the margin of the inland-ice, Drs. Brennecke and Heim made measurements of temperature of the air at head height above the surface of the snow of the inland-ice, also at the snow surface itself and, further, at a depth of 10 cm. (4 in.) below it; these measurements being taken three times daily for a

[36] The Holm expedition along the southeast coast of Greenland in 1883–85 carried out at Nanortalik comparative studies of air temperature above the snow, and of the snow itself at the surface, observations being made at intervals of four hours throughout one winter season. These were not made, however, over inland-ice. The temperature of the snow was found to be two or three or more degrees lower throughout. The large variations in the temperature of the air were found to be accompanied by corresponding variations in that of the snow. The temperature of the rocky ground was also measured at the surface and at depths of 12 and 20 inches at intervals of four hours daily from November to April. The air temperatures were invariably lower than those of the rock and the rock temperatures at the lower levels were still higher by one or two degrees. As was to be expected, the rock temperatures fluctuated much less than those of the air (H. Holm, "Den Ostgrönlandske Expedition udfort i Aaren 1883–85," *Med. om Grönl.*, vol. 9, 1889, pp. 407–408).

Ångström made studies of snow and air temperature differences in comparison with effective radiation during the polar night at Abisko, and he found that the temperature difference was in general proportional to the radiation (Anders Ångström, "On the Radiation and Temperature of Snow and the Convection of the Air at its Surface, *Arkiv för Mat., Astron. och Fysik,* Stockholm, vol. 13, No. 21, pp. 18. See also A. Ångstrom "On Radiation and Climate," *Geogr. Ann.*, 1925, pp. 122–142).

period of three and a half days. Observations of the air temperature, which included also the wind direction and the relative humidity, were carried out simultaneously upon the ship. To quote Barkow on the results:

> These observations are, despite their brief continuation, already very instructive; since, among other things, they show that the air above the inland-ice is on the average noticeably colder than over the ship distant a few kilometers only and at the time drifting in the Vahsel Bay. On the 1st of March at 9 P.M. the air at the height of the eye above the inland-ice was colder by full 6° C. and the temperature of the surface yet lower by about 1 1/2°. In the mean for all cases the inland-ice was colder by about 2° in a height above sea of only 45 m., and the temperature on the surface itself is, in fact, a round 3° lower. There is present, then, already in the season of the late summer a noticeable temperature inversion over the inland-ice (p. 122).

Lauge Koch's studies in North Greenland. — Dr. Lauge Koch, after much experience along the borders of Greenland, made in 1921 a crossing of the inland-ice from Independence Fjord on the northeast coast to Washington Land at the southwest. This section is at an average elevation of about 1000 meters, but crosses the undulating near-marginal portions of the dome at a somewhat lower level than the routes of Peary and Rasmussen (see Fig. 46).

There is in this part of Greenland a marginal ribbon of high mountainous country between the inland-ice and the sea-ice of the Arctic Ocean. Dr. Koch reports:

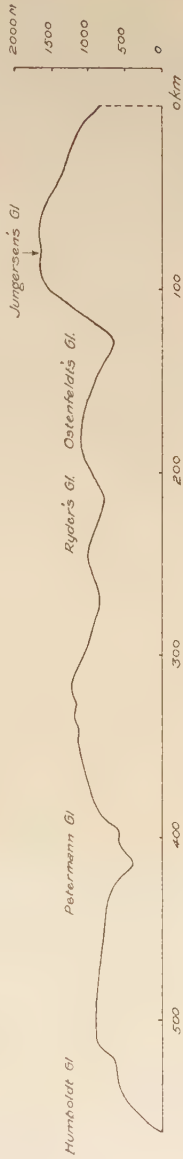

Fig. 46. Profile along the route of Koch in 1921 across northern Greenland (supplied by Dr. L. Koch)

The anticyclone blowing downward and outward over the ice-dome is here not as strongly marked as in other parts of Greenland because of the much flatter surface of the inland-ice. Further, it seems as though the wind that blows constantly in an outward direction from the interior of Greenland, as is so clearly shown on Knud Rasmussen's map and profile of 1917, does not blow, or scarcely ever blows here, below the 1000 meter contour line. Whenever I had ascended beyond this level, the wind blowing outward from the ice-cap grew more violent the higher I ascended; though this wind never reached my camps within the depressions. Neither did the wind blow through these depressions during the winter, as was shown by the state of the snow. This corresponds very well with my observations made both in 1917 and in 1921 within the north coast fjords, where the snow-cover in the spring is quite level, and in which winds blowing inward from the fjords are never observed. On the margin of the ice-cap in the neighborhood of the Petermann Fjord and the low part of Dangaard-Jensen Land, which together form a communication trench for winds from the Kane Basin to Robeson Channel and *vice versa*, we encountered winds which did not come from the interior of Greenland (see map showing wind directions, Fig. 47).[37]

There appears to be a suggestion of similar pockets of stagnant air in the " steppe " region southeast of Holstensborg, west Greenland, as described by Otto Nordenskjöld. When northerly winds prevailed on the coast, here behind the coastal mountains calms were noted though the prevailing winds came off the inland-ice from the southeastward.[38]

Of other protected pockets which are on the northwestern coast of Greenland we have the testimony of another explorer: [39]

It is interesting to note that in the inner reaches of Inglefield Gulf and its inner tributary fjords, the wind rarely blows hard at any time in the whole winter, and the snow lies rather deep, soft, and unpacked for weeks, even months, at a time. Kangerdlugsuak at the very head of the gulf is a place of calm air and clear sky. Likewise, the broad expanse of Kane Basin along the foot of the Humboldt Glacier, is relatively calm, and in general Melville Bay is not swept by high winds from the bordering ice-cap. On the other hand, Wolstenholme Sound and Grenville Bay,

[37] Personal communication from Dr. Koch to the author which he is authorized to publish.

[38] Otto Nordenskjöld, " Einige Züge der physischen Geographie und der Entwickelungsgechichte Süd-Grönlands," *Geogr. Zeitsch.*, vol. 20, 1914, Heft 8, pp. 513–514.

[39] W. Elmer Ekblaw, who has supplied the paragraph with permission to publish.

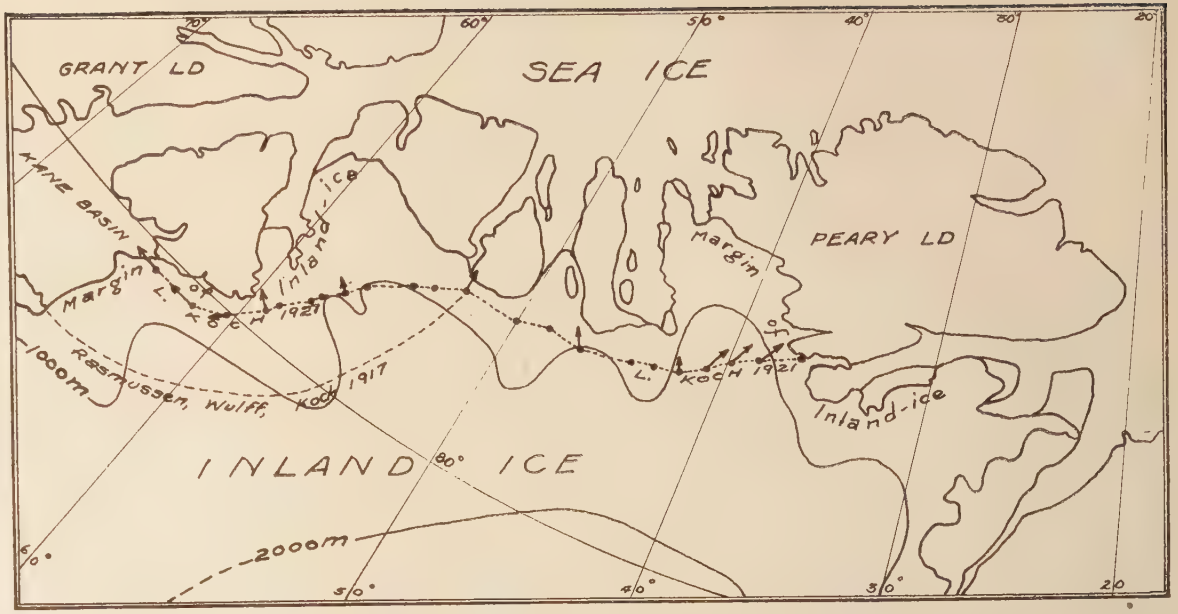

FIG. 47. Map of the route of Lauge Koch across the inland-ice of North Greenland showing wind directions. The length of the arrow is proportional to the force of the wind, and locations given without arrows indicate absence of wind (supplied by Dr. Koch).

between Melville Bay and Inglefield Gulf, are characterized by high winds blowing toward the sea, and Etah, which lies on Foulke Fjord, between Inglefield Gulf and Kane Basin, gets its name from the high winds that blow down that fjord. In Foulke Fjord the prevailing direction of the wind on the ice-cap or the bordering plateau matters not; it may be south or north, or east or west above, but in Foulke Fjord it blows southwestward from the ice-cap to the sea.

Nordenskjöld's monograph on Antarctic ice. — A monograph on the Antarctic ice by so distinguished a polar explorer as Professor Nordenskjöld is of much importance in this study, for though his explorations did not take him over the inland-ice of the Antarctic, his long sledging expedition to King Oscar Land brought him to its borders, and a member of his expedition, Dr. J. Gunnar Andersen, crossed the narrow belt of inland-ice of West Antarctica. In a forthcoming monograph which has been long in type but delayed in publication, speaking of the Antarctic Continent, Dr. Nordenskjöld says:

> Above this cold region lies, as it appears, a permanent anticyclone [see on the glacial anticyclone W. H. Hobbs in *Proc. Amer. Philos. Soc.*, vol. 54, 1915] which gives rise to the stormy south winds which control along much of the continental margin.[40]

Data from the Norwegian meteorological station at Mygbugten, east Greenland. — At Mygbugten (Mackenzie Bay) on Franz Josef Fjord, east Greenland, the Norwegians established a meteorological station equipped with wireless and in regular communication with their station on the island of Jan Mayen. This station was maintained from October, 1922, until August, 1923. I am indebted to Director O. Krogness, who is in charge of the Norwegian Arctic meteorological work, for the following valuable data:

The station was situated upon a great plain or in the bottom of a wide valley near the shore of Mackenzie Bay (lat. 73° 30.5′ N. and long. 21° 30′ W.). The position of the margin of the inland-ice is northwest of the station and it takes a direction

[40] Communicated to the author with permission to publish.

which is in general northeast-southwest, as is clearly seen from the official map [41] (Fig. 48).

The full meteorological data were lost on the ship, of which nothing was later heard, but certain data had already been re-

FIG. 48. Map of the vicinity of the Norwegian Station at Mygbugten (Mackenzie Bay), reproduced from the official map by the Danish Government

ceived by telegraph and from these Mr. O. Edlund has kindly prepared at the request of Dr. Krogness the following table of wind frequencies, which I have been authorized to publish:

[41] Kort over Grönland udgivet af Commissionen for Ledelsen af de Geologiska og Geographiska Undersögelser i Grönland, Copenhagen, 1906, Scale 1 : 2,000,000.

MYGBUGTEN 1922–23

PERCENTAGE FREQUENCY OF WINDS

Month	N.	NE.	E.	SE.	S.	SW.	W.	NW.	C.	N. & NW.
Sept.	14.5	3.5	6	2	0.5	0	3.5	26	0	72.3
Oct.	42	13	8.5	3	2	5	14	35.5	1	63
Nov.	53	17.5	7	3	1	1.5	9	28	0	67.5
Dec.	32.5	14	18.5	5	6.5	7.5	15	24	1	45.9
Jan.	42.5	9	15	5.5	6	5	12.5	27.5	1	56.9
										Ave. 61.1
Feb.	19	8.5	25	14.5	8	6	10.5	17.5	3	
Mar.	16.5	14.5	25.5	20.5	5.5	2.5	21.5	14.5	3	
Apr.	15	6	20.5	24	7.5	11	17.5	16.5	2	
										E. & SE.
May	13	3	19.5	34	16	10	13.5	11	4	44.4
June	4	3	21.5	62.5	13	5	7	3	1	70
July	7.5	2	23.5	65	5.5	3.5	9	7	1	71.4
Aug.	1	1	19.5	25.5	2	3	3	1	0	80.4
										Ave. 66.5

From these data it appears that during the months September to January there is a dominance of winds from the north and northwest, and these are clearly down-slope winds blowing off the inland-ice lying to the northwest deviated in a clockwise direction by earth rotation. For the summer months of May to August, on the contrary, a no less definite dominance by east and southeast winds is demonstrated, and these, as clearly shown by the fuller data which indicate the direction of shift, arise from cyclonic disturbances arriving from the Greenland Sea. Here, as at other fjord-head stations on the margins of Greenland,[42] is located the common border of inland anticyclone and ocean cyclone, the margin undergoing migrations with the seasons. The fuller daily record, which supplies wind force as well as wind direction, brings out the strophs of the anticyclone, particularly during the winter months.

[42] See the volumes of the *Meteorologisk Aarbog,* Copenhagen.

Flight of Commander Byrd over the inland-ice of northwest Greenland. — The pioneer in exploring inland-ice by means of airplane is Lieut.-Com. Richard E. Byrd, Jr., U. S. N., who on August 22, 1925, flew an estimated distance of about forty miles in a direction a little south of east from Igloodahouny (50 miles south of Etah), northwest Greenland. On this flight an altitude of 11,000 feet was believed to have been attained "over a part of the ice-cap never before explored, and we saw in the direction we were going that it reached an altitude equal to that of the plane — 11,000 feet — higher than any altitude heretofore reported."[43] Such a high elevation in this vicinity was hardly to be expected, and it will require verification through landing or by some other confirming method.

"We could see 100 miles in every direction. As we got farther in over the ice-cap it grew bitterly cold, although at 7000 feet we had encountered a warm stratum of air." He expressed his belief that except in the crevassed marginal portion a plane equipped with skis could land.

[43] Richard E. Byrd, Jr., "Flying over the Arctic," *Nat. Geogr. Mag.* vol. 48, Nov., 1925, p. 532.

CHAPTER X

THE GENERAL ATMOSPHERIC CIRCULATION

THE "POLAR FRONT" THEORY OF BJERKNES

Marks the abandonment of Ferrel for Von Helmholtz. — As concerns theories of atmospheric circulation within the high latitudes, the period since 1920 has seen a general abandonment, at least by European meteorologists, of the fundamental conception of Ferrel for that of Von Helmholtz. The former treated the polar regions as though they were entirely passive respecting irradiation, the circulation within the region being regarded as the result of earth rotation acting upon the air currents which arrive from lower latitudes. Von Helmholtz, on the contrary, conceived the polar regions to be areas of high irradiation because of a cold surface, above which cold air would mound up and flow off toward lower latitudes.

Assuming this to be true, Bjerknes on the basis of extended and very brilliant investigations of meteorological conditions in Europe and over Norway in particular, has built up his theory of the "polar front." As has been shown, the work of all explorers who have brought back observations from the north polar region shows clearly that the region is one of peculiarly normal air-pressure (see Chapter III).

Outline of the theory. — The general acceptance of the theory of Bjerknes makes it important to have it presented in outline here, and this will be done very largely by use of his own words: [1]

[1] V. Bjerknes, "On the Dynamics of the Circular Vortex with Applications to the Atmosphere and Atmosphere Vortex and Wave Motions,"

On each hemisphere there are four circulations running as toothed wheels, the circulation of the trades, the circulation of the temperate zone, the circulation of the polar east wind zone, and the circulation of the theoretically polar west wind zone. The first and the third of these circulations represent thermodynamically direct cycles, in which the motion is maintained by heat energy. But that of the temperate zone is an indirect cycle, by which kinetic energy is transformed into heat, and the same should be the case with the polar west wind zone.

These circulations give two zones of descending motion, where very limited precipitation should be expected, namely a zone round the pole, and the zone of the sub-tropical calms; and, further, two zones of ascending motions and great precipitation, one along the equator, and one along the polar front, situated on the polar side of it. Finally, a third theoretical zone of precipitation should be at the pole itself, but of no physical importance as shown below.

In whatever way the air from the south enters the polar region,[2] continuously or intermittently, it must arrive with a westerly motion, which it cannot lose before it has descended to the ground and begun its motion southwards: this leads to the consequence often referred to, of a tendency to form a west wind region nearest the pole. But it is not probable that this ever leads to independent development of a central polar cyclone (pp. 86–87).

In a later publication the polar aspect of this theory is much more clearly elucidated by J. Bjerknes and Solberg, and illustrated for the north polar region: [3]

The source of energy for the general circulation of the atmosphere lies in the contrast of temperature between the polar and the equatorial regions. The system of motion which is comprised under the name "General Circulation," tends to smoothe this contrast by bringing polar air to tropical regions, and vice versa. . . . The "trade wind" from the pole divides into different branches — polar currents — between which channels remain open to corresponding branches of the anti-trade — tropical currents. Thus the "antitrade" of the temperate zone appears not only as an upper polewards current but also as "tropical currents" on the ground.

Geofysiske Publikationer, vol. 2, no. 4, Christiana, 1920. See also "Die Atmosphäre als zirkularer Wirbel, Ergebnisse der aerologischen Tagung vom 3. bis 6 Juli 1921 im Preusz. Aeronaut. Observ. Lindenberg," *Beitr. z. Physik d. frei Atmosph.*, 1922, pp. 15–19.

[2] Obviously the north polar region is here meant.

[3] J. Bjerknes and H. Solberg, "Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation," *Geofysiske Publikationer*, vol. 3, No. 1, Utgit av den Geofysiske Kommission, Kristiania, 1922, pp. 18.

The particular polar currents will, when starting as northerly currents, tend to deviate into NE or even ENE currents; likewise the tropical currents deviate from southerly to SW or WSW currents. We thus have a system of alternate polar and tropical currents beside each other, winding up spirally round the axis of the earth (see Fig. 49).

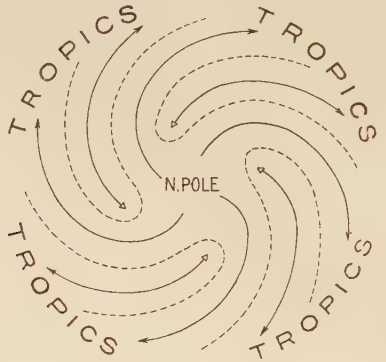

Fig. 49. General scheme of atmospheric circulation over the Northern Hemisphere (after J. Bjerknes and H. Solberg)

The polar front theory is well set forth in an article by Von Ficker, who says of it:

> The views which today taken together may be designated as Polar Front Theory are based upon the assumption from the facts of observation that over the polar region there is a piling up of cold air which on all sides is separated from the surrounding warmer air masses, either by a surface of discontinuity or by a transitional layer.[4]

Observational basis in northwestern Europe only. — The Bjerknes theory of atmospheric circulation, as thus appears from the monographs, has been arrived at on the basis of observations made exclusively in Europe and peculiarly in Norway. It takes no account of observations which have been made either in Greenland or within the Arctic region proper which surrounds the North Pole. A mass of cold air, the authors believe, moves out over Europe from some area to the northwest

[4] E. von Ficker, "Polarfront, Entstehung und Lebensgeschichte der Zyklonen," *Met. Zeitsch.*, Jahrg. 40, March, 1923.

and is separated by a surface of discontinuity from warmer air on its southern border; but we know that no such high pressure

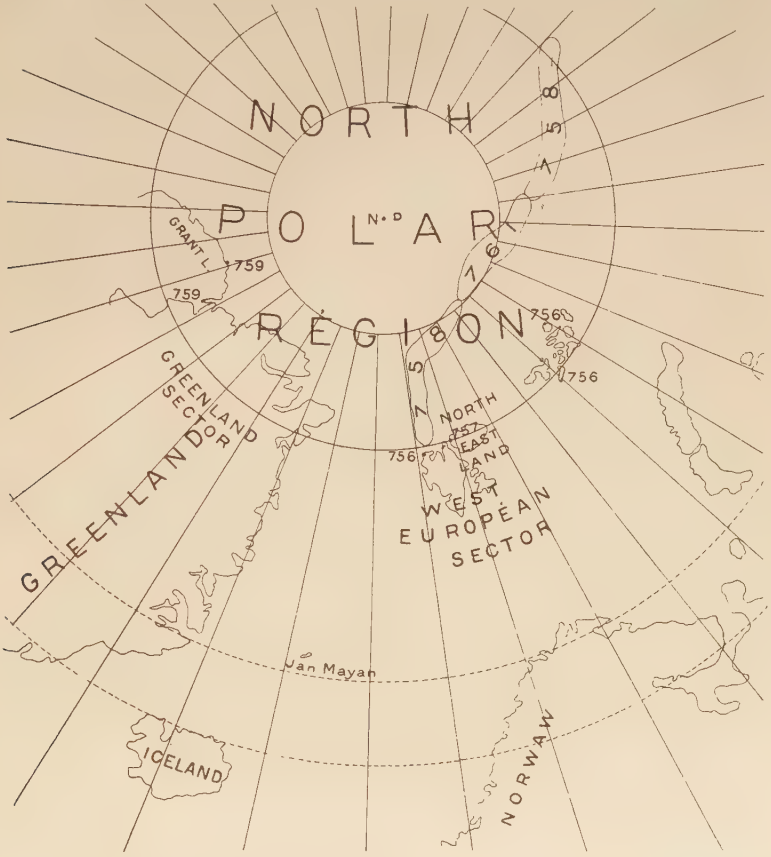

FIG. 50. Map of the north polar region and portions of adjoining European and American sectors to show the distribution of mean annual atmospheric pressure

area as the theory requires lies over the north polar region (see Fig. 50).[5] We know that the air temperatures above the polar

[5] See Chapter III.

basin are, in fact, very much lower than would be expected from the latitude. As a matter of fact, temperatures in the latitude of 85 degrees North are very much higher than those experienced in the winter in Montana and neighboring portions of British America. The truth of such a statement is borne out by the experience of all polar explorers over the Arctic Sea. At points on the coast of Siberia and British North America during the winter season, northerly winds generally bring with them an elevation of air temperature while southerly winds bring a lowering of the temperature. Kindle has assembled data from many sources to prove this.[6]

The unique large area of high pressure north, northeast or northwest of Europe lies above the continent of Greenland, is bounded near its coasts, and sends off vast masses of cold air during the strophs of the glacial anticyclone.

Air from "polar front" resembles that from Greenland.— Bjerknes refers to the polar front which he has mapped as the "line of demarcation between polar and equatorial air Jan. 1, 1907," and he says:

> Though we have been able to draw the line only half round the pole, there can be no doubt that it surrounds the polar regions as a closed circuit. On the north side of this line all signs indicate air of polar origin; it has a low temperature for the latitude, shows great dryness, distinguishes itself by great visibility and has a prevailing motion from east and north.[7]

Now the glacial anticyclone lying over Greenland has outlines which curiously enough are parallel in a general way to the bulging out to the southward of the polar front as Bjerknes

[6] R. M. Kindle, "Observations on Ice-borne Sediments by the Canadian and Other Arctic Expeditions," *Am. Journ. Sci.,* (5) vol. 7, 1924, pp. 253–257.

[7] V. Bjerknes, "The Meteorology of the Temperate Zone and the General Atmospheric Circulation," *Nature,* vol. 105, June 24, 1920, pp. 522–524

has drawn it across the Atlantic Ocean; and, further, the foehn winds which issue from it have just the characteristics so definitely portrayed by Bjerknes for his "polar front" air in the lines last quoted. Such air is quite different from that encountered by explorers within the north polar region of frozen sea.[8] The air about the North Pole instead of being colder than would correspond to the latitude is very much warmer (see p. 150). It is by contrast the air which has descended from a high plateau. Moreover, the winds of the true polar region do not blow outward toward Europe. The experience of Nansen indicates that the polar winds are extremely variable in direction. Mohn's tables appear even to show a preponderance of winds of a southerly component over those with a northerly component.

Cyclone families of northwestern Europe generated in Greenland. — There are, moreover, in the characteristics of the cyclone families other relationships of much significance which the Bjerknes have been able to work out in detail within the Norwegian area. These cyclone families usually consist of from three to six individual cyclones in succession, of which four only can, as a rule, be observed from any single point of observation, for the reason that their paths are not identical, the later ones traveling on paths somewhat farther south than their predecessors.

These cyclones within a family group are designated A, B, C, D and E, and sometimes F, the leading cyclone being A. The first pair within the series, A and B, possess characteristics

[8] Rains and fogs were frequently encountered by Nansen during his cruise in the *Fram*. Fogs are recorded for all months except December, January and February. There were 66.5 days of fog in the year (Mohn, *op. cit.*, pp. 536–537). All subsequent explorers have confirmed this view. Amundsen's greatest foe during his flight toward the pole was the fog which hid the surface below.

which show them to be relatively old. They are sluggish in their progression and apparently in a dying condition, which is interpreted to mean that they have traveled far. Cyclones C and D by contrast travel more rapidly, have greater vigor and are regarded as of younger age. "We may from this draw the conclusion," say J. Bjerknes and H. Solberg, "that A and B cyclones are formed relatively far west of Europe, and have traveled for several days before they reach us, whereas *C and D cyclones are formed nearer to the European network of stations*" [9] [italics not in original].

If E and F cyclones develop, they are so much the more vigorous than even cyclones C and D. There appears, therefore, to be a definite progression in cyclone intensity from A and B through C and D to reach a culmination in E or F, when the series comes abruptly to an end. This is the characteristic of the evolving stroph of the anticyclone (see Chapter VII).

There is, moreover, in the paths pursued by individual cyclones of the family a further evidence of the crescendo of vigor which characterizes the family. The weak cyclone A generally pursues its course northward over Norway into the Arctic region. Cyclones B and C being more vigorous steer to the right and pass over Sweden and Finland. D cyclones veer still farther to the right and pass over Denmark, southern Sweden and the Baltic. E cyclones, if formed, may deviate still farther to the right. In these characteristics there is apparently a confirmation of the reality of the cyclone cycles as they have been worked out by the Norwegian meteorologists.

If the migrating cyclones have approached the coast of Greenland with the characteristics which they possessed when they left the United States, they differ little, if at all, from

[9] V. Bjerknes and H. Solberg, "Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation," *Geofysiske Publikationer,* vol. 3, No. 1, 1922, p. 14.

each other; for it is not without significance that though cyclone families have easily been recognized in Europe, they have not been in the United States.[10]

The destructive cyclones of Europe sent out during the stroph of the anticyclone. — The great volume of air which pours out from the Greenland inland-ice during the stroph of the anticyclone, at the surface and in the lee of the ice-cap, halts abruptly, just at the contact with the migrating cyclones along the coast. At higher levels this in its outward movement must certainly pass upward within the adjacent migrating cyclones,[11] and it must impart to them a vigor which near the ground will increase as they travel. Cyclones A and B, it would appear, have passed the Greenland ice-dome during a calm between strophs; C and D during the evolution of a stroph and are rejuvenated in consequence; whereas E and occasionally F (the cyclones which cause destructive storms over Europe) have been generated during the climax of the stroph of the glacial anticyclone. When a new stroph is inaugurated, a new family of cyclones is generated. Upon this interpretation C and D cyclones should perhaps be regarded as beginning the series, A and B having been generated not on the coast of Greenland but far to the westward.

Bjerknes says that in the period from January 1 to November 23, 1921, no less than 59 cyclone families in succession crossed the line from south Greenland to Norway. A cyclones he has named " Arctic " because they travel over northern Norway. The devastating hurricane which passed over Denmark on October 23, 1921, was an E cyclone.

Thus far it has generally been found impossible to give warning of the coming of these younger and destructive members of the cyclone family " because they are often formed rela-

[10] See A. J. Henry, *Monthly Weather Review*, Sept., 1922, pp. 468–474.
[11] See Lockyer reference as cited on p. 164.

tively close to the European coast."[12] The lately founded station on the island of Jan Mayen in the Greenland Sea has not been able to give the warnings in time,[13] and V. Bjerknes has urged the importance of a wireless meteorological station on the southern point of Greenland. If the author's view be correct, a better position for such a station is to be found farther north upon the coast of Greenland opposite the broader portion of the ice-dome, and this station should be located at an elevation of about 3000 feet because the outrushes of air override the lower air strata on the borders of the continent.

Greenland foehns (strophs) synchronize with passage of strong cyclones along coast. — There is evidence from Greenland that the strong foehn winds which mark the culmination of each stroph of the anticyclone are coincident in time with the passage of stronger cyclones along the coast. As long ago as 1889 Jantzen, treating of the foehns encountered by the Holm expedition, connected the time of arrival of the foehn winds at the southeast coast with the passage of strong cyclones. So close was the connection in time that Jantzen was forced to believe that the passing lows caused the foehns to blow down from the interior of the continent. "*One finds then,*" said he, "*that it is the lows moving to the east of Angmagsalik which produce the foehn, the atmospheric current from the north and northeast* [the fall wind from the plateau] *being a derivation of the winds of the east and southeast on the coasts north and east of the lows, and taking on the foehn characteristics as they pass below the mountains*"[14] [his italics].

[12] V. Bjerknes, "The Importance of Wireless Weather Reports from Greenland," *Month. Weath. Rev.*, Jan., 1922, pp. 16–18.

[13] "During the period December 1, 1919, to March 15, 1920, between 70 and 80 storms occurred at that part of the Norwegian coast, for which the forecasts at that time were issued from Bergen. No less than 22 of these storms were either not predicted or the issued warnings were too late to be effective. I must add that these unwarned storms on the average were the most violent" (V. Bjerknes, *op. cit.*, p. 17).

[14] Holm, *op. cit.*, p. 406.

That keen and experienced student of Greenland, Dr. Rink,[15] long ago wrote of the west coast, "When the southeast wind [glacial anticyclone], has blown itself out, there follows as a rule wind coming straight from the south and through the Davis Strait [cyclone], frequently as a storm. . . ." This view has been confirmed by later observers, notably by Stade.[16]

THE AUTHOR'S THEORY

From the last section it is apparent that the author's studies of the Greenland glacial anticyclone are in complete harmony with the studies by the Bjerknes and Solberg of the cyclone families in Europe. The one theory is fitted to the other as are the teeth of geared wheels. Alone the cold air which rejuvenates the dying cyclones on their approach to the coast of Europe from the west, instead of having a polar origin, issues from the Greenland Continent during a stroph of the anticyclone.

Asymmetry of the wind poles of the earth. — In previous chapters the striking parallels which exist between the atmospheric conditions above the earth's two continental glaciers have been pointed out. These northern and southern glacial anticyclones fixed in position, function as the loci of drainage from the upper wind currents and are therefore the reversing positions within the general cycle of air movement — they, and not the geographic poles, are the wind poles of our planet. How nearly in correspondence with the southern geographic pole the southern wind pole may be, we do not yet know; and it will be necessary to await the results of future sledging trips based upon the Luitpold and Adelie coasts before this question can be satisfactorily answered. It is clear, however, that its position is much less eccentric than is the northern wind pole, which is removed no less than nineteen degrees of latitude from the end of the earth's axis.

[15] H. Rink, *Grönland*, 1860.

[16] *Op. cit.*

Northerly displacement of the equator of circulation. — In representing the general circulation of the earth it becomes necessary to show differences for the different hemispheres. An attempt to represent the eastern portion of the Western Hemisphere without account being taken of the effect of position of the land and water areas within moderate latitudes has been made in Plate I (*Frontispiece*). In this map, which is purely schematic, the much greater dimensions of the Antarctic anticyclone and the lack of symmetry in this part of the earth's circulatory system become at once apparent. Such lack of symmetry had already been shown by the surface distribution of atmospheric pressures on all modern charts. Thus the narrow equatorial belt of the doldrums is displaced northward on the average by about seven degrees of latitude and the northern tropical belt of calms and high pressure by about the same amount. The prolonged series of studies made with pilot balloons combined with observations of the directions of motion of the cirrus clouds made on the equator in Java have confirmed this observation from charts, that the isobaric highs range farther north than they do south of the equator.[17]

The preponderance of the land areas within the Northern Hemisphere and of the seas within the Southern Hemisphere, is, of course, in large part responsible for this lack of symmetry where the isobars cross the continents. The same lack of symmetry extends, however, to the oceanic areas as well, and the position of the Greenland wind pole should make just such a difference between the eastern and western portions of the Northern Hemisphere. The greatest contrast should be found to characterize the meridians of 40° W. and 140° E., since they make up the great circle which bisects the continent of Greenland in a north and south direction. It is, in fact, near this

[17] W. Van Bemmelen, "The Antitrades," *Nature*, Feb. 9, 1922, pp. 172–173. See also references to the author's papers as cited in Note on page 1.

great circle that are formed the greatest contrasts within the oceanic areas, and they are of such a character as to give Greenland a more or less central position. The effect of the northern land areas about the narrower Atlantic Ocean should tend, were this the sole cause of displacement, to produce the opposite result.

The striated character of the surface circulation of air within the zones of the middle latitudes is in harmony with the work of modern students of cloud direction.[18] By the use of colors and through adding a section of the troposphere along the meridian of the center of Greenland (40° W.), it is hoped that the general scheme of atmospheric circulation as it is here conceived will be made intelligible (see *Frontispiece*).

[18] Cf. Bigelow, *op. cit.*, and also J. Bjerknes and H. Solberg, *op. cit.*, 1922, pp. 14–15.

CHAPTER XI

GLACIAL ANTICYCLONES OF THE PAST

THE INCEPTION OF THE GLACIAL ANTICYCLONE

The embryonic phase. — In the last paragraph reference was made to the view of Von Helmholtz revived by Bjerknes and others, that over high latitudes or over a snow cover a differential surface radiation is sufficient to account for a gradual mounding up of cold air to produce outward flow and indraft above; and that this would bring about fixed anticyclonic conditions within the air which overlies the region. Naturally in case this region were elevated and occupied in part by mountain glaciers, and if the snow-line were at a sufficiently low level, ice-caps like those of Norway and Iceland or of the outlying high areas about the Greenland inland-ice would be formed.

Circulation above the Vatna Jökull, Iceland. — In southeastern Iceland is found the great Vatna Jökull, an ice-cap which rises to a height of about 1900 meters and covers an elliptical area of nearly 8000 square miles. The late Dr. Th. Thoroddsen in his time was the best authority upon this great shield of snow and ice, and he gave it as his opinion that no permanent anticyclone is located above it.[1]

Circulation over northwest Spitzbergen. — Northwestern Spitzbergen is covered by the peculiar type of glacier which Nordenskjöld has described as the Spitzbergen type,[2] a glacier of generally flattish domed form from which the peaks of the

[1] Personal communication to the writer.

[2] Otto Nordenskjöld, *Die schwedische Südpolar Expedition und ihre Tätigkeit*, Stockholm, 1911, p. 178.

largely submerged alpine highland project as rocky islands, *nunataks*. It is to be expected that such a glacier, within which there are many outflowing ice streams between the mountain peaks, should have a centrifugal air circulation. In recent years this interesting area has been mapped with great care and represented with contour lines on the surface of the glacier itself.[3] Those who have worked on or near the glacier have confirmed the down-slope circulation of the air,[4] the strong foehn winds at the fronts of the glacier outlets, and the violent winds which go out for a short distance only within the fjords. Werenskiold[5] has noted that the vigor of the anticyclonic circulation above the glacier stands in a special relationship to the passing low pressure areas, the latter appearing to "suck out" the air along the glacier outlets which act as canals.

Circulation above Northeast Land, Spitzbergen. — In the narrative[6] of the sledge-journey made in 1873 across the large ice-cap of Northeast Land, there seems to be found the evidence of more or less anticyclonic conditions of circulation, as I pointed out in 1911.[7] The significant facts may profitably be

[3] Maps prepared by the Mission Isaacson in 1906–7 and issued by the Videnskaps Akademie, Oslo.

[4] For the character of the glacier surface see Adolf Hoel, "Observations sur la vitesse d'ecoulement et sur l'ablation du glacier Lillehöök au Spitzberg 1907–12," *Videnskapsselskapets Skrifter, I Mat. Naturv. Klasse,* 1916, No. 4, Carte 1 and plate 1. See also Kurt Wegener, "Einiges aus den Ergebnissen der Schröder-Stranz-Expedition (Die Kontinentale Hochdruckgebiet Spitzbergens)," Veröff. des Deutsch. Observatoriums Ebeltofthafen-Spitzbergen, herausgegeben von H. Hergesell, Lindenberg, 1916, 2 Heft, pp. 12–14; G. Rempp und A. Wagner, "Die Hydrodynamik des Föhns und die 'lokalen Winde' in Spitzbergen," *ibid.,* 1917, 7 Heft. pp. 1–11; C. S. Elton, "The Dispersal of Insects to Spitzbergen," *Trans. Entom. Soc. London,* Aug. 7, 1925, pp. 289–299.

[5] W. Werenskiold, "Spitzbergens fysiske geografi," *Naturen,* June-August, 1920, pp. 210–211.

[6] A. E. Nordenskiöld, "Die Schlittenfahrt der schwedischen Expedition in nordöstlichen Theile von Spitzbergen, 24 April — 25 Juni, 1873," *Pet. Met.,* vol. 19, 1873, pp. 451–452; A. Leslie, *The Arctic Voyages of Adolf Erik Nordenskiöld 1858–1879,* with illustrations and maps, London, 1879, p. 257.

[7] *Characteristics of Existing Glaciers,* pp. 276–278.

recounted here. The ice-cap rises into a dome from the margin, and after the first day's journey the party ascended over an even and almost imperceptible slope to a plain which had an altitude of 2000 to 3000 feet above the sea. Fine hard snow was found to be almost constantly in motion along the surface of the glacier, which was glazed and polished by its action. Under ordinary weather conditions this stream of rounded snow grains rose a few feet only into the air, but even then it was most troublesome. Much snow was being transferred over the surface, and when the party emerged from the tent in the morning, sledges were found concealed beneath a great drift.

After the first day's journey, during which the weather was clear, either snow storms or dense snow mists were the rule. Several times during the journey Nordenskiöld observed the remarkable phenomenon described below.

There occurred a highly peculiar fall of:

1. Small round snowflakes, sometimes resembling stars, of a woolly appearance.

2. Grains falling simultaneously, of about the same size as the snowflakes, but formed of a translucent irregular ice-kernel, surrounded by a layer of water, which, however, froze in a few moments after the fall to ice, and in a short time covered our sledge sail, &c., with a thin and smooth crust, or fastened itself on our hair and clothes as small translucent ice-drops. During one such fall on the 5th June there were seen *simultaneously* a faint halo and a common rainbow, the temperature being 4° to 5° C. under the freezing point. That a fall of ice mixed with water can take place with so low a temperature is clearly due to the fall being derived from a stratum of cloud formed of over-cooled watery vapour, that is to say, formed in part of small drops of water cooled under the freezing point, but still fluid.[8]

Viewing this phenomenon in the light of our knowledge of the glacial anticyclone, one is inclined to explain the ice-kernels found to be enveloped in a film of water as ice-grains, and to account for the film by surface fusion of these grains through the adiabatic effect of downdraft within the interior of an anticy-

[8] Leslie, *op. cit.*, p. 255.

clone. This phenomenon was observed when the needles of ice were within the surface layer of air cooled by contact with the cold glacier surface, and hence they were at once congealed. The source of the associated soft snow in the star-like crystals would appear to be those ice-grains which have been fully vaporized. The presence of ice-grains and condensed moisture together in the atmosphere would explain the halo and the rainbow which were observed simultaneously.

In the summer of 1924 the Oxford University Arctic Expedition under Binney made explorations in Northeast Land and found that the ice-cap over this island has two distinct domes separated by Wahlenberg Fjord and its continuation eastward as a sag of the ice-cover. One sledging party crossed the southern dome from east to west, a second party penetrated well toward the center of the northern dome from the west coast, and a third sledging party made a double crossing of the western portion of the northern dome.[9] The geologist, Mr. K. S. Sandford, is strongly of the opinion that the air circulation above Northeast Land is anticyclonic except when the region is invaded by a strong cyclone. Says Sandford: "It is clear that there is a definite outward flow of air from the northern ice dome which was visited by the northern and central sledging parties. This was maintained during the period of sledging (July 22–Aug. 15) except for a few days (Aug. 6–8) when a strong depression . . . seems to have overcome local conditions in Northeast Land. . . . There is no doubt as to the outward flow of air, and as such it performs the chief function of a glacial anticyclone, i.e., radial transport of snow. . . ." (p. 119)

Sandford has supplied descriptions of other interesting char-

[9] F. G. Binney, "The Oxford University Arctic Expedition, 1924," *Geogr. Journ.*, vol. 66, July and August, 1925, pp. 9–40, 111–134, Map ("Geology and Glaciology and Air Conditions," by K. S. Sandford, with air conditions on pages 119–126).

acteristics of this ice-cap. The blizzard of August 11 occurred when all three sledging parties were on the ice and widely separated from one another, two of them on the north dome and one of them on the southern dome. This blizzard, as shown by the diaries of the leaders, stopped at the same time at all three localities, at which the wind directions were quite different though in each case down the slope of the ice. The beginning of the blizzard, however, was noted in succession by the three parties and in such order as to show that anticyclonic conditions became reëstablished as the strong low pressure area passed off to the northeast.[10]

With rising pressures the air passes out radially on the dome with sun, clear sky and frost, and with showers of fine ice crystals so minute as to penetrate the pores of the clothing.

Circulation over the ice-cap of Novya Zemlya. — About the borders of the ice-cap which overlies the northern island of Novya Zemlya, outward blowing winds are the rule, according to information communicated personally by Professor Olaf Holtedahl of the Norwegian expedition to Novya Zemlya.

Circulation over the ice-caps on Ellesmere Land. — On Ellesmere Land there are large ice-caps which have been visited by explorers. Professor W. Elmer Ekblaw, now of Clark University, was geologist and botanist of the Crocker Land Expedition of 1913–17, and he made sledging trips about some of these ice-domes. He has prepared the following statement concerning the air circulation near them with permission to publish here. It will be noted how well this circulation corresponds to that of other ice-domes already referred to:

> On the Grinnell Land Ice Cap lying between Princess Marie Bay, which projects far into Ellesmere Island from the east, and Greely Fjord, almost a hundred miles farther north, which projects just as far into the island from the west, there is distinct evidence of a radiating flow of air from the central portion to the peripheral borders, particularly down the

[10] Personal communications to the author.

glacier tongues extending out through high-walled valleys. This outward flow of air is most pronounced when the wind is moderate; in times of calm, when the air on the ice-cap seems inert, a gentle breeze moves down the slopes of the ice-cap; in times of high wind from either east or west on the ice-cap, the deeper, more protected valleys on the windward side are relatively calm, while those of the leeward side are troughs of accentuated wind velocity; this antithetical effect of the leeward and windward valleys, tends to emphasize the apparent peripheral movement of the wind — the high winds from either east or west are accentuated on the leeward side and subdued on the windward side. The in-blowing winds are not so readily noticed or remembered; the outblowing winds are both noticed and remembered. Low pressure areas produce wind conditions strikingly similar to those of middle latitudes, though they seem to recur more frequently, and pass more quickly.

Between the ice-caps of Ellesmere Land the depressions seem to be belts of generally calm conditions These are particularly noticeable in Bay Fjord, Beitstadt Fjord, and in the northwestern expanse of Greely Fjord and the basin of Lake Hazen.

POSSIBLE CAUSES OF THE SECONDARY ICE-DOMES ON CONTINENTAL GLACIERS

We have already seen that the inland-ice of Greenland has at least two separate but coalescing domed summits, a fact first made certain when the profiles of Nansen, De Quervain and Koch had become available. The two known domes of the Greenland glacier Dr. Lauge Koch has explained by the existence of two original gneiss plateaus separated by a depression which crosses from Disco Island on the west coast to a point on the east coast south of the main salient of this latter coast.[11] A similar explanation would probably account for the separate domes of the ice-cap of Northeast Land.[12]

There have been too slight penetrations of the continent of the Antarctic (see Fig. 24, p. 62) to enable one to speak with any assurance of even its marginal portions, but the penetration

[11] L. Koch, "Some New Features in the Physiography and Geology of Greenland," *Journ. Geol.*, vol. 31, 1923, pp. 62–64, fig. 4.

[12] See F. G. Binney, *op. cit.*

by David to the Magnetic Pole Plateau when compared with that of Scott in the region southwest of McMurdo Sound during his first expedition, and Mawson's expedition from the Adelie Land base, indicate with some probability that a secondary dome of this continental glacier is located above the Magnetic Pole Plateau, and that this has a crest considerably below the level of that crossed by Scott on his last expedition. Moreover, the elevations which were attained by Armitage on his sledge-journey over inland-ice along a line somewhat to the south of Scott's route at that time.[13] were much higher than those obtained by Scott on a much deeper penetration, and these observations seem to point to a small secondary dome somewhere to the southward of Armitage's route.

A distribution of these secondary domes for the Antarctic Continent was suggested by the writer in 1915,[14] and these suggested domes are indicated upon the map of the Antarctic region reproduced in Figure 51. The introduction upon this map as an essential part of the circulation of this part of the world of the procession of cyclones according to Lockyer's view[15] puts into strong light the contrasts which exist between the Northern and the Southern hemispheres as regards the general atmospheric circulation. It has already been shown by several authorities, for Greenland first by Rink, and clearly brought out for the Antarctic by our representation of the wind observations made by Wilkes (see p. 7, Fig. 3), that mighty as is the glacial anticyclone, its domination at the surface seems to wane and disappear at relatively small distances from the inland-ice margin. Such a condition is, we believe, fully accounted for if

[13] A. B. Armitage, *Two Years in the Antarctic,* Arnold, London, 1905, Chapter X.

[14] *Proc. Am. Phil. Soc.,* vol. 54, 1915, p. 223, fig. 10.

[15] W. J. S. Lockyer, "Southern Hemisphere Air Circulation, etc.," Solar Physics Committee under direction of Sir Norman Lockyer, London, 1910, pp. 109, pls. 15.

the outward downdraft of the permanent anticyclone is updrawn at once into the migrating cyclones which encircle it. This enormous contribution to their vigor makes of this zone sur-

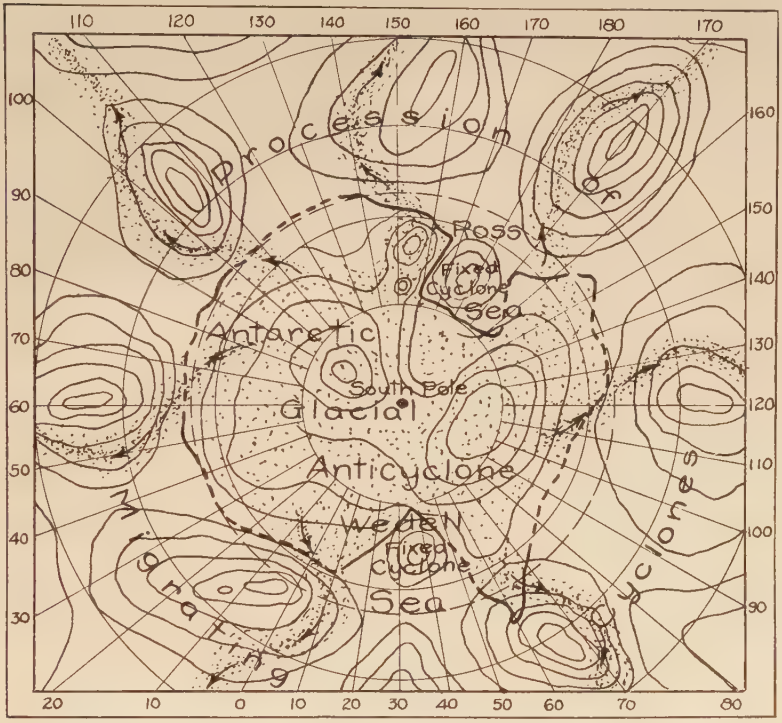

FIG. 51. Suggested distribution of secondary domes on the inland-ice of the Antarctic, together with the permanent cyclones above the Ross and Weddell seas. The continuous procession of low pressure areas which migrate in clockwise fashion around the great glacial anticyclone of the Antarctic Continent are also given after Lockyer.

rounding the Antarctic that of the "roaring forties" and "screeching fifties." Mawson's data also have shown clearly that on the borders of the inland-ice of Adelie Land, the air ascended in "whirlies" and that the great climaxes of the

glacial anticyclone of that region were felt in remote Australia and in fact preceded by about forty-eight hours the arrival of storms on the Australian south coast.[16]

If now we turn to consider the Pleistocene glacier of the North American Continent, we find here also the evidence of at least four domes and centers of radiation, two main and two subordinate; and these have become known respectively as the Keewatin (west of Hudson's Bay), the Labradorean (east of Hudson's Bay), the Patrician (north of Lake Superior) and the Newfoundland centers (Fig. 52).[17] Concerning these domes Leverett has shown that though they came to culmination at different times, they also existed simultaneously. Culmination of glaciation appears, moreover, to have arrived first at the main eastern center and to have migrated westward across Hudson's Bay to the western or Keewatin center. This explanation takes, however, no account of the glacial anticyclone as a means of nourishment.[18]

PAST CLIMATES IN RELATION TO THE GLACIAL ANTICYCLONE

The present an abnormal period in earth history. — The climatic zones which are so important a factor of the present and are distributed in the main with regard to latitude, appear on the basis of geological observations of the first importance to be a quite abnormal incident in the long history of the earth. Today within low latitudes near the equator we find a zone of high insolation and of excessive evaporation, of strong upward movement of air currents which carries the ceiling of the troposphere to an extreme altitude of 18 to 20 kilometers. Adiabatic transformations connected with this stupendous convectional process lock up in the form of ice-particles a considerable pro-

[16] Mawson, *The Home of the Blizzard,* vol. 2, 1914, pp. 141, 157–158.

[17] See Hobbs, *Proc. Am. Phil. Soc.,* vol. 54, 1915, pp. 190–193, fig. on page 192.

[18] Frank Leverett, "Pleistocene Deposits of Minnesota and adjacent Districts," *Bull. Geol. Soc. Am.,* vol. 27, 1916, pp. 68–69.

FIG. 52. Domes and centers of radiation on the Pleistocene continental glacier of North America

portion of the moisture carried into the air, and these are transported poleward at high levels as the cirrus clouds and their modifications. A portion only of these air currents and their sealed-up moisture appears to be brought to earth within the horse latitudes, the remaining portion being carried on beneath the descending ceiling of the troposphere to higher latitudes and eventually to the glacial anticyclones.

The "circumpolar cyclones" — cyclones only in the sense that the vortex assumed involves motions inward toward its axis, not in respect to the vertical movement, which was anticyclonic — were the part of the Ferrel scheme of atmospheric circulation regarded as necessary to bring these upper currents down to earth and return them equatorward and keep them within a continuous cycle of movement. It now appears that the return mechanisms of the general circulation within high latitudes, instead of being "circumpolar whirls," are the great glacial anticyclones located over Greenland and over the Antarctic Continent. The one *wind pole* of the earth is centered not remote from a geographic pole, whereas the other has taken position with its center removed some nineteen degrees of latitude from the opposite pole. The atmospheric circulation is given its vigor at the present time not alone through a pushing upward of currents within the tropics as a consequence of excessive insolation within that region, but also by a pulling down by the refrigerating engines of the continental glaciers.

As every glacialist is aware, the present is in reality the waning phase — receding hemicycle — of the Pleistocene glaciation, one of the three great periods of continental glaciation which are known in the entire earth history.[19] The other periods are, doubtfully, the late Pre-Cambrian or the early Cambrian, and the Permo-Carboniferous or Permian.

[19] Other periods are known which were characterized by smaller glaciers, but of none is it supposed that continental glaciation existed.

Within the Permian period, so far as moderate latitudes are concerned, glaciation was chiefly developed within the Southern Hemisphere, whereas in the Pleistocene the glaciation of moderate latitudes was within the Northern Hemisphere. Of the older period referred to, the extent of the glaciation is involved in a good deal of uncertainty, though it apparently was characteristic of both Northern and Southern hemispheres. During both the Permian and the Pleistocene geological periods there were vast continental glaciers in addition to those which were located over the Antarctic and Greenland[20] (see Fig. 19b, p. 53). The influence of these vast domes of ice in stimulating a vigorous circulation must have been of the utmost importance, and the zonal distribution of climates should in consequence have been so much the more pronounced.[21]

The geological past generally devoid of marked climatic zones. — It has long been known, though more widely recognized in recent years, that the distribution of certain fossil plants and animals shows that the migrations of these delicate organisms in the geologic past were not barred by climatic zones as they are today. In 1910 the matter was treated for the field of paleobotany by two of the most distinguished of American paleobotanists, Drs. David White and F. H. Knowlton.[22] Their joint summary statements are so important that they are given below:

1. Relative uniformity, mildness (probably subtropical in degree), and comparative equability of climate, accompanied by a high humidity, have prevailed over the greater part of the earth, extending to, or into, the

[20] Presumably there was glaciation of these areas since there were ice-sheets in lower latitudes.

[21] W. H. Hobbs, "The Pleistocene Glaciation of North America in the Light of our Knowledge of Existing Continental Glaciers," *Bull. Am. Geogr. Soc.*, vol. 43, 1911, pp. 641–659, fig. 9.

[22] David White and F. H. Knowlton, "Evidences of Paleobotany as to Geological Climate," *Science*, N. S., vol. 31, 1910, p. 760. See also G. F. Matthew, "Were there Climatic Zones in Devonian Times?" *Proc. and Trans. Roy. Soc. Can.*, 3rd Ser., vol. 5, 1911. Sec. IV, pp. 125–153.

polar circles, during the greater part of geologic time since, at latest, the Middle Paleozoic. This is the regular, the ordinary, the normal condition. From a broad point of view these conditions are relatively stable.

2. The development of strongly marked climatic zones, at least between the polar circles, is exceptional and abnormal. It is usually confined to short intervals, or to intermittently oscillating short intervals, all within relatively short periods.

3. The periods of abnormal climatic differentiation are characterized by the development of extremes — i.e., by extreme and abnormal heat or cold (glaciation), humidity, or aridity — which are local or regional in their occurrence and variable or unstable.

4. The brief geological period in which we live is a part of one of the most strongly developed and unstable of these abnormal intervals of radical change. The assumption that climatic variations, contrasting extremes, and complexity of combination and geographic distribution of climatic factors, such as now exist, are normal or essential, and that they were present also, though in slightly less degree, in all geological periods appears to be without paleobotanical warrant. The proposition that we are still in the glacial epoch is paleontologically true. We have no evidence that in any other post-Silurian period, with perhaps the exception of the Permo-Carboniferous glacial period, have the climatic distribution and segregation of life been so highly differentiated and complicated as in post-Tertiary time.

5. The development and existence of torridity — i.e., of a torrid zone in the equatorial belt or any other great region of the earth — is concomitant and causally connected with the development of regional frost. It would appear that the occurrence of a torrid zone is peculiar to abnormal or glacial intervals.

In 1915 I first drew attention to the significance of these facts as they relate to the anticyclones above continental glaciers.[23] In 1919 Dr. Knowlton took up the subject with some thoroughness[24] and after discussing the several geological periods individually he said in summary:

It is perhaps not too much to say that it has now been demonstrated beyond reasonable question that climatic zoning such as we have had since the beginning of the Pleistocene did not obtain in the geologic ages prior to the Pleistocene. I think this statement of conditions is very

[23] "The Ferrel Doctrine of Polar Calms and its Disproof in Recent Observations, *Proc. Second Pan-American Scientific Congress,* Washington, Sec. II (*Astronomy, Meteorology and Seismology*), vol. 2, pp. 184–187.

[24] F. H. Knowlton, "Evolution of Geologic Climates," *Bull. Geol. Soc. Am.,* vol. 30, 1919, pp. 499–566.

generally accepted by geologists and paleontologists — in fact, I am at a loss to know how the data available can be otherwise interpreted (pp. 537–538).

Dr. Charles Schuchert also in discussing the climates from the point of view of a paleontologist who has studied the animal life of the past, says: [25]

> The marine 'life thermometer' indicates vast stretches of time of mild to warm and equable temperatures, with but slight zonal differences between the equator and the poles. The great bulk of marine fossils are those of the shallow seas, and the evolutionary changes recorded in these "medals of creation" are slight throughout vast lengths of time that are punctuated by short but decisive periods of cooled waters and great mortality, followed by quick evolution, and the rise of new stocks. . . . On the land the story of the climatic changes is different, but in general the equability of the temperature simulates that of the oceanic areas. In other words, the lands also had long-enduring times of mild to warm climates.

It is certainly most significant that the past record of the earth should reveal with such clearness that it is only within the two relatively brief geological periods of extensive glaciation of the inland-ice type that strongly developed climatic zones existed; and the conclusion is therefore forced upon us that the stimulation of the circulatory system by the downdraft over vast ice-domes of continental dimensions has been the directly actuating cause (see Fig. 19a and b., p. 53).[26]

[25] Charles Schuchert, "Climates of Geologic Time," *Smith. Rept.*, 1914, pp. 277–311.

[26] Obviously the recent work of Köppen and Wegener (*Die Klimate der geologischen Vorzeit*, Borntraeger, Berlin, 1924, pp. 255, 1 pl. and 41 figs.) ignores these facts, for these authors assert (p. 2), "that in all times in the history of the earth the same climatic zones have existed." It is perhaps significant that they also state (p. 1), "In this book the prehistoric changes of climate will be considered under the assumptions of the theory of continental sliding which is here regarded as right."

CHAPTER XII

PRESENT OPINION AND FUTURE RESEARCH

PRESENT-DAY METEOROLOGICAL OPINION

The explorer versus the meteorologist. — Our survey of the course of meteorological thought in what concerns that part of the earth's general circulation which is, very broadly speaking, within the polar regions, has indicated that before either of the great polar continents had been penetrated the circulation above them had been fully visualized through speculation; and that this foreordained scheme of circulation had been but little affected by the advance of observational knowledge during three quarters of a century.

Explorers who have penetrated the polar continents have without exception brought back the evidence for a superimposed mechanism of circulation quite different from that which speculation had visualized; and quite generally the explorers themselves have interpreted their observations to indicate centrifugal slope winds.

Quite otherwise has it been with the school of meteorologists. Ignoring the vital difference between the north and the south polar regions proper — the northern polar area a level expanse of sea covered by floating ice-floes, the southern a continent deeply buried beneath a flat dome of ice and snow — they have in their discussions treated both as though these polar areas were identical, and until quite recently as though the antiquated theory of "polar calms," "polar cyclones" and "circumpolar whirls" were in harmony with observed fact. Today we know that the north polar area proper — that surrounding the geo-

graphic pole — which by Ferrel was visualized as a low pressure area and by Bjerknes as one of high pressure, is characterized neither by high nor by low, but by nearly normal air pressures; and that the great inland-ice dome about the southern pole is paralleled in the Northern Hemisphere by a quite similar ice-dome which envelops the continent of Greenland located in an eccentric position centered fully nineteen degrees from the geographic pole. These vast domes absolutely control the circulation above them, and the atmospheric poles of the earth, quite unlike the geographic poles, are centered above the polar continents, and one of them is in a highly eccentric position as are both the magnetic poles of the earth.

Any attempt to treat the general atmospheric circulation of the earth while failing to recognize these essential facts can lead only to error. It must also be emphasized that our qualitative knowledge today is fairly complete for the continent of Greenland though relatively scanty for that of the Antarctic. So far as meteorologists have modified their earlier views concerning the circulation of polar regions, it has been almost exclusively with reference to the Antarctic. The great reservoir of pertinent data from Greenland has been left almost untouched.

Interpretation of local as regional winds. — Reference has been made to the rather general interpretation of winds at base stations in the Antarctic, as though these were of a regional character, and it is on this assumption that the elaborate computations of Meinardus are based. Since, however, these are of purely local significance, serious misunderstanding has been occasioned and it is entirely due to this that there is a widespread belief that the marginal winds of the Antarctic are always southeasterly (see p. 29). In reality they have a southeasterly direction, with certain exceptions, only when the course of the margin of the continent is from east to west.

Accident determined that the base of the *Southern Cross* expedition of 1899–1900 should be located on the west side of the narrow Cape Adare peninsula under the edge of the inland-ice and at a point where the slope of the glacier rose in an east-southeast direction; and so the dominant winds were from the east-southeast (Fig. 53, a, b and c). Less than three hundred miles away to the southwest, but on the opposite side of this peninsula, was located in a later period the winter refuge of the Priestley party of Scott's last expedition. Here the slope of the inland-ice which lay to the westward ascended in that direction, and so the dominant wind direction was exactly opposed or west-northwesterly (Fig. 53, d).

The later British expeditions made their base upon the eastern shore of McMurdo Sound within a sluiceway for the air, which because of earth rotation piles up on the westward side of the Ross Barrier; and the wind comes from the southeast for the simple reason that the sluiceway takes that course. The dominant winds of the neighborhood are, however, from the southwest, and these winds take over control with all greater blizzards (Fig. 53, f). This condition is brought out particularly well at all points where outlet glaciers from the inland-ice of South Victoria Land make junction with the flat and low-lying Ross Barrier (Fig. 53, e and Fig. 21, p. 57).[1]

It has already been shown (p. 30 and Fig. 7) that the southwesterly winds controlled summer and winter alike at the Norwegian base of Nordenskjöld in West Antarctica.

Austrian and German opinion. — As already developed in detail in the foregoing pages, Professor Hann, the leading authority of our times on meteorology and climatology, early set himself stoutly in opposition to the newer interpretations which inevitably were made on the basis of observations by Antarctic

[1] C. S. Wright and R. E. Priestley, "British (Terra Nova) Antarctic Expedition," *Glacialogy*, figs. 2, 4 and 5, pp. 14–17; R. E. Priestley, *ibid.*, "Physiography (Robertson Bay and Terra Nova Bay Regions)," map II in pocket of cover; F. Debenham, *ibid.*, "The Physiography of the Ross Archipelago," Fig. 1, p. xii.

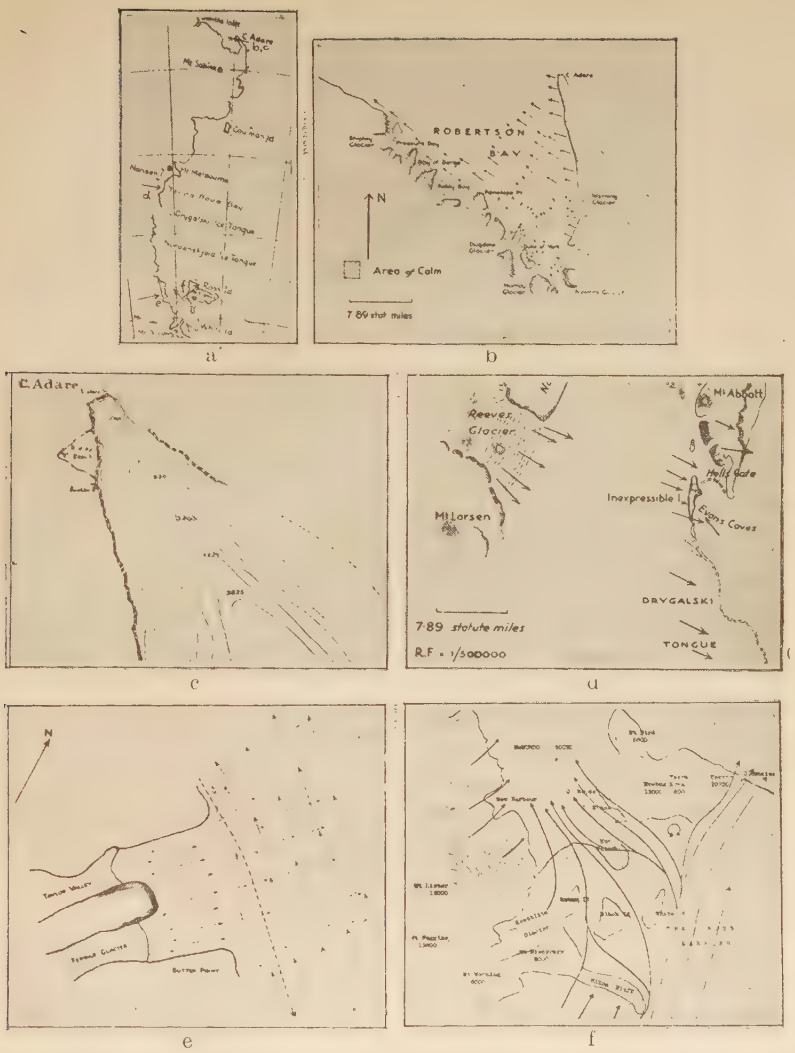

FIG. 53. Maps to show the local character of the prevailing winds as determined at the several British stations in South Victoria Land. (a) General map to show the relative positions of the bases at Cape Adare, Terra Nova Bay, and McMurdo Sound; (b) Prevailing E.S.E. winds at Cape Adare (after Wright and Priestley); (c) Inland-ice contours near the Cape Adare Base on Ridley Beach (after Priestley); (d) Prevailing winds at Priestley's base at Terra Nova Bay (after Wright and Priestley); (e) Map showing junction of southwesterly down-slope winds from the inland-ice with the southerly Barrier winds west of McMurdo Sound (after Wright and Priestley); (f) Southeasterly sluiceway winds of McMurdo Sound and the dominant southwesterly down-slope winds from the inland-ice (after Debenham).

explorers who had brought back knowledge of conditions of circulation over and near to the inland-ice — observations which were clearly in opposition to the Ferrel speculation concerning polar conditions of circulation. This stand of Hann was also upheld by Meinardus on the basis of extensive computations from pressure and temperature observations which had been made by various expeditions at stations surrounding, but outside, the Antarctic Continent. As the evidence continued to pile up, Hann held his ground doggedly and to the time of his death in 1923 would not admit the existence of an anticyclonic circulation over the Antarctic, but only upon its borders. His treatise on meteorology is now, since his death, being revised and rewritten by Professor Süring, head of the German Chief Meteorological Station at Potsdam, but with no essential change of attitude in this respect.[2] In Chapter V (*Lieferungen* 6–7) issued during the present year (1924–25), the general atmospheric circulation is treated wholly without reference to the glacial anticyclones.

In treatises issued since 1920 the Bjerknes theory of the polar front and of the cap of cold air over the North Pole is almost universally introduced. Professor Exner of Vienna, director of the Central Institute for Meteorology and Geodynamics, in his treatise entitled *Dynamical Meteorology,* has also ignored the existence of glacial anticyclones.[3] A new edition of this valuable work, which appeared in 1925,[4] is much enlarged and rewritten, and while recognizing the influence which the Bjerknes views have had, Exner sets up a theory of atmospheric circulation of his own, which he refers to as a reversed polar front theory. He has, however, the same idea of the iden-

[2] Hann-Süring, *Lehrbuch der Meteorologie,* 4te umgearbeitete Auflage, Tauchnitz, Leipzig, Lieferung 7, 1924, pp. 487–506.

[3] Felix M. Exner, *Dynamische Meteorologie,* Teubner, Leipzig-Berlin, 1916, pp. 308.

[4] Published this time by Julius Springer in Vienna.

tity of the two polar areas and of the cold air reservoir about the North Pole which is bounded by the "polar front." He says of the polar regions:

> The observations on the earth's surface show from about 70° of latitude on, a new increase of pressure toward the pole, which, as a cold reservoir, takes part in a sort of convection flow with the lower latitudes. . . .
>
> The cold air which flows off from the poles becomes quickly east wind. . . . (p. 223)

Two recent German works on the atmospheric circulation also ignore the results of all recent work in the polar regions.[5] Defant says that "the cold air masses of the polar regions cover over like a cap the higher latitudes. . . ." (p. 140)

British opinion. — The views of Sir Napier Shaw, lately the director of the British Meteorological Office, have already been referred to, since he supplied the preface to the volume on meteorology of the first Scott expedition to the Antarctic and followed closely the lead of Hann in placing a cyclone above a shallow anticyclone encircling the Antarctic region (see p. 121). In a book which issued from the press in 1923, Shaw treated the general circulation as "polar and equatorial" with consideration of circumpolar whirls and of weak anticyclones over the Atlantic and Africa, but not, strange to say, over Greenland and the Antarctic.[6]

The views of Simpson, who has now succeeded Shaw as director of the Meteorological Office, have already been given with some fullness (pp. 124–132). Simpson has not taken account of the relationship of air circulation to the topography

[5] Alb. Defant und Erich Obst, "Lufthülle und Klima," *Enzyklopädie der Erdkunde,* herausg. von O. Kende, Deutiche, Wien, 1923 (reprinted from *Beitr. z. Physik d. f. Atmosphaere*); Fr. Ahlborn, "Die drei grossen Zirkulationen der Atmosphaere," *Beitr. z. Physik d. frei. Atmosphaere,* vol. 11, 1924, pp. 117–153.

[6] *The Air and Its Ways,* Univ. Press, Cambridge, 1923, pp. 237, especially pp. 151–154.

within the Antarctic region and has followed much the same direction as Hann and Shaw. In his latest publication the two polar regions are treated as playing identical rôles in the atmospheric circulation with no reference whatever to Greenland.[7]

Geddes, lecturer at the University of Aberdeen, in a recent treatise,[8] after referring to the high pressure areas in the temperature zones, says: "Beyond these belts pressure diminishes towards both poles, regularly in the Southern Hemisphere, but irregularly in the Northern" (p. 113).

Griffith Taylor, assistant professor of Geography at the University of Sydney and the geologist of the last Scott expedition, in his *Australian Meteorology* has fallen into the common error concerning the supposedly prevailing southeasterly winds of the Antarctic continent, for he says: [9]

> Surface winds around the Antarctic and on the latter continent are chiefly from the south-east, where they constitute the famous blizzard winds. . . . There is a permanent region of high pressure at the south pole, and the winds blowing from the pole to the low-pressure belt at 66° S. follow the same rules as does the trade wind.

French opinion. — French thought has been less hampered by authoritative pronouncements, and the French expeditions to the Antarctic have been restricted in their studies to the areas of sea-ice. The French explorers have treated but little the air circulation over the Antarctic Continent. The one authoritative French treatise on meteorology is that by Angot, last revised in 1916.[10] Angot has treated the north polar region without reference to Greenland and as probably representing a minimum of

[7] G. C. Simpson, "The New Ideas in Meteorology," *British Assoc. Adv. Sci.* Sect. A, Southampton, 1925, President's address, pp. 1–15, issued Aug. 28, 1925.

[8] A. E. M. Geddes, *Meteorology*, Van Nostrand, 1921, pp. 390.

[9] Griffith Taylor, *Australian Meteorology*, a text-book including sections on aviation and climatology, Clarendon Press, Oxford, 1920, pp. 101–102.

[10] Alfred Angot, *Traité Elementaire de Météorologie*, Gautier-Villars, 3rd ed., revised and corrected, 1916, 415 pages.

pressure, but for the Antarctic he has recognized the work of explorers as indicating an anticyclone. He says:

> It is reasonable that in consequence of the dynamic effect of which we have spoken the minimum of pressure is found exactly at the pole; it is probable that this is the case for the Northern Hemisphere, but it is conceivable that it is something else. If there existed all about the pole a great continent extremely cold, the action of the temperature might become preponderant; in this case, the pressure, after having diminished rapidly between the latitudes 35° and 60° or 70°, would augment anew toward the pole, which would therefore be the center of an anticyclonal movement presenting in the layers near the ground a divergent movement with a component directed from the pole toward the equator. It is this which the recent observations taken in the Antarctic region appear to indicate . . . (p. 155)

Although no later treatise of an original character dealing specially with meteorology or climatology has appeared in France, the new edition of De Martonne's standard *Treatise on Physical Geography* has an entire part devoted to climate, which part comprises two hundred and twenty-six pages, and the book has been rewritten throughout.[11] Of the polar régime De Martonne says:

> Mohn had already after the Nansen Expedition been able to lay out the pressure maps over the Arctic polar basin, indicating a tendency to the formation of an anticyclone in summer over Northern Greenland and Spitzbergen; while in winter a bridge of pressures relatively high should join the maximum of Siberia with that of Manitoba in North America, low pressures reigning to the east and the west of Greenland.
>
> The circulation is certainly, here as in the temperate zone, strongly influenced by the division of land and sea. According to Hobbs, glaciation itself should play a rôle, and the ice-dome of Greenland, the same as the Antarctic continent, should cause a refrigeration of the lower layers of the atmosphere sufficient to produce an anticyclone. In fact, one has always established the divergent winds on the coasts of Greenland (S. E. on the west coast, and N. W. on the east coast). It appears to be established that North Greenland is throughout the year included in an anticyclonic area. The west winds do not penetrate far into the polar basin, and they are replaced in summer, even on the Siberian coast, by winds from the east.

[11] Emm. de Martonne, *Traité de géographie physique,* 4ème edition, entierèment refondu, vol. 1, Paris, 1925, pp. 496.

It is in the southern hemispheres, always more regular than the northern hemisphere, that one is tempted to seek the normal conditions of circulation. But the Antarctic polar region is occupied by a continent almost as vast as Europe with a mean altitude of more than 2000 meters and covered by a cap of ice. It was early recognized that the strong west winds of the Antarctic Ocean are replaced beyond 65° latitude by winds of polar origin. Simultaneous observations have permitted Meinardus to establish the reality of a system of divergent winds around the Antarctic continent. The greater part of the year an anticyclone certainly controls; a furrow of low sub-arctic pressures appears to exist between 60° and 70° of latitude; it should be this which determines the moist east winds which supply the great falls of snow on the advances to the Antarctic continent (pp. 169–170).

American treatises and texts. — A considerable number of recent American treatises and texts have appeared but without taking account of the actual conditions of circulation within high latitudes.[12]

Huntington and Visher in their recent volume discuss the glacial anticyclone.[13] The circulation of the winds for both Greenland and the Antarctic they have set forth correctly, but they have misinterpreted my theory of alimentation of the continental glacier, following in this the lead of Hann, Meinardus and others. Here they have distorted the facts concerning the anticyclone in a new direction and have made an attempt to explain the alimentation of the glacier through deposition of snow by cyclones along the borders. The high humidity of the interior regions is rather amusingly set aside in the following manner: "Hobbs reports that explorers in Antarctica and

[12] W. J. Milham, *Meteorology, A Text-book on the Weather, the Causes of Its Changes and Weather Forecasting for the Student and General Reader,* Macmillan Co., 1912, pp. 549, 50 charts, diagrams.

Frank H. Bigelow, *A Meteorological Treatise on the Circulation and Radiation in the Atmosphere of the Earth and of the Sun,* Wiley, 1915, pp. 431.

J. H. Clayton, *World Weather, etc.,* Macmillan Co., 1923, 393 pages, illustrated.

Jacques W. Redway, *Handbook of Meteorology,* Wiley, 1921, 294 pages.

[13] E. Huntington and S. S. Visher, *Climatic Changes, Their Nature and Causes,* Yale University Press, New Haven, 1922, pp. 329.

Greenland have frequently observed condensation on their clothing. If such moisture is not derived directly from the men's own bodies it is apparently picked up from the ice sheet by the descending air and not added to the ice sheet by air from aloft" (p. 137).

A further misconception of the nature and cause of the anti-cyclone probably accounts for the following statement: "If Hobbs' anti-cyclonic hypothesis of glacial growth is correct, it would appear that ice sheets should grow up where the temperature is lowest and the high-pressure areas most persistent; for instance, in northern Siberia" (p. 137). It is necessary to remind these authors that these conditions should persist throughout the year.

Professor McAdie, in a recent treatise,[14] is not entirely clear in his references to atmospheric conditions near the poles. On page 56, referring to Ferrel's theory of circulation, he says:

> The circulation, as outlined, requires marked depressions around the poles, whereas, in reality, an entirely different distribution of pressure exists.

On page 63, however, speaking for himself, he says:

> Again the west-east drift of the atmosphere in middle and higher latitudes forms a gigantic polar cyclone.

In 1915 when my monograph on "The Rôle of the Glacial Anticyclone" was in manuscript, Professor Humphreys of the U. S. Weather Bureau was at my request good enough to read the manuscript critically. In his *Physics of the Air*, published in 1920, he has given in the main an excellent treatment of the glacial anticyclones of Greenland and the Antarctic.[15] Under the caption "General Circulation" his significant paragraphs are:

[14] Alexander McAdie, *The Principles of Aerography*, Rand McNally, Chicago, 1917, pp. 318.

[15] W. J. Humphreys, *Physics of the Air*, Lippincott, 1920, pp. 665.

There are two extensive regions, Antarctica and Greenland, where the barometric pressure always is high.[16] At each place the high pressure appears to be the result of the very low prevailing temperatures, which in turn are due in part to the great elevations and in part to the free and abundant radiation from the snow surface through the comparatively clear skies kept generally free from clouds by the descent of the upper air induced and maintained by the vigorous fall winds. That surface radiation is an essential factor in establishing and maintaining these low temperatures is obvious from the fact that air cannot flow down hill, as it does in these regions, unless it has a greater density and therefore lower temperature than the adjacent atmosphere of the same level. It is also obvious from the prevailing and excessive surface temperature inversions, in which, and because of which, those ice fogs that doubtless furnish much of the interior precipitation are so common.

It will be well to remember in this connection that snow, in addition to reflecting about 70 per cent. of the incident solar radiation, is also a good emitter of those long wave-length (12–15 μ) radiations appropriate to its temperature. In this way the low temperatures are maintained, not only during winter when air circulation and, to some extent, cooling ice supply the only available heat, but also during the long-continued insolation of summer.

The air drainage thus produced is manifest in those strong and persistent southeast[17] or anticyclonic winds that characterize the climates of the border and all explored portions of Antarctica, except, of course, near the pole, and, presumably, therefore, of the whole continent. Similar, though less vigorous, anticyclonic winds also prevail over and around Greenland. Each of these great regions, but especially Antarctica, by virtue of its strong and continuous refrigeration, obviously is exceedingly effective in its influence on the atmospheric circulation of its respective hemisphere. If there were no such extensive high and snow-covered areas in the polar regions, it is clear that our general circulation would be less vigorous and doubtless very different in many places.[18]

On page 609 under the caption "Other Factors of Climatic Control," there is found in the main a particularly good summary of my theory of the glacial anticyclone:

. . . when the slope is very gentle, as it is over the interior of Greenland and over much of the explored portion of the Antarctic Continent,

[16] This is of course inferred only on the basis of the prevailing winds. We have no barometric data which can be used, since we have as yet no position upon either continental glacier for which the altitude has been determined by other than barometric methods. We have always the insoluble single equation of two variable quantities.

[17] Southeast only when the margin follows an east and west direction.

[18] *Op. cit.*, pp. 198–200. Humphreys has here fallen into the usual error concerning the southeast winds of the Antarctic border.

air drainage necessarily is sluggish and unable to keep pace with the surface cooling. Hence, in such cases the change of temperature with change in elevation (counting from sea level) can be, and usually is, far greater than adiabatic, or 1° C for 100 meters. Hence, such regions, when there are no higher surrounding mountains, can and often do establish: (1) a circulation of the upper air from the ocean to the higher portions of the plateau; (2) a well-defined surface temperature inversion, or, for the first few hundred meters, an increase of temperature with increase of elevation; (3) a slow settling of this air onto the cold surface below; (4) the precipitation, without cloud, of fine snow crystals — "frost snow"; (5) drainage of this chilled and relatively dense air to lower levels; (6) drifting of the snow with the winds and the consequent extension, so far as temperature and other conditions will permit, of the ice-covered or glaciated area.

All these conditions obtain today over the two great glaciers that still remain, that of Greenland and that of Antarctica, and, presumably, therefore, must also have obtained to a greater or less extent over all great glacial fields wherever and whenever found.

It has seemed necessary to furnish extracts in some fullness from the more recent meteorological treatises in order to show how generally their authors have ignored the existence of the great Greenland continential glacier with its powerful anticyclone; and, further, how they have likewise ignored the evidence from observation of generally normal air pressures over the north polar region. Humphreys is the one noteworthy exception to this rule.

For treatment of the glacial anticyclone the plan which has been chosen is the historical one, since this method seemed the only way of bringing into clear light the genesis of those traditions which have been so potent a factor in this as in most fields of science — traditions which are usually connected with some one or more of the great figures in the history of the science. In any attempt to explain the origin of those grooves along which as concerns the general circulation of the atmosphere opinion has been made to flow, it will be found that the homage generally paid to systematic observations has been responsible for much of the error. Extrapolations have been depended upon to take the place of direct observation upon the

ground, and elaborate computations have been carried out on the basis of data derived in reality from a different system of circulation.

From the great continental glaciers themselves direct observations of wind direction made during sledge-journeys have now been available for periods varying from a quarter to half a century, yet these data have quite generally been ignored by the meteorological profession and conclusions have been based wholly upon the observations carried out at base stations. This procedure, a rather general tendency to treat meteorological questions on a mathematical basis, and the battle to defend the erroneous speculations of Ferrel; these explain the failure to appreciate either the nature or the importance of the two vast glacial anticyclones as major elements in the general atmospheric circulation.

SUGGESTIONS FOR FUTURE RESEARCH

Quantitative to replace qualitative studies. — As one surveys in retrospect our observational knowledge of the glacial anticyclone, it is impressed upon him how largely qualitative is this evidence. The time has now come, it is believed, when more quantitative studies must be undertaken, if we are to pursue our inquiries with profit.

Dimensions of the anticyclone. — The lines of future inquiry are in part clearly indicated, and certain of them relate especially to the dimensions of the circulatory system which the glaciers control. To what height above the surface of the ice-dome do the outstreaming air currents — the lower portion of the anticyclone — extend, and at what rates do their velocities fall off with altitude? At what elevation is found the neutral zone of equilibrium above which the direction of motion is reversed? How does the velocity of these upper instreaming air currents change with altitude, and at what height does the

anticyclonic circulation come to an end? What are the directions and what the rates of movement of the clouds included within the system?

What is the average diameter of the area of downdraft over the interior of the dome, and what maximum and minimum values correspond to the culmination and to the beginning of the anticyclonic stroph? What are the summer and the winter means and extremes for this diameter? Just how far out from the margin of the dome does the anticyclonic circulation extend, and how do these limits vary with the phases of the strophic movement and with the season? How is this indication of anticyclonic vigor related to the approach of the migrating cyclones which pass along the borders, and how is each vortex modified through its contact with the other? Are these vortices of opposite kind sensibly attracted to each other?

Problems of insolation and radiation. — Suitable technical methods must be discovered for measuring accurately and continuously the in- and out-radiation at the snow-ice surface of the glacier, and there must be a check through comparison with the humidity of the air and its further content of snow-flakes, ice-crystals and water droplets. Simultaneous studies must be made to determine the temperature curve for depth within the snow-cover of the glacier. Of great importance is here the quantity of the included air, and any indication of a fusion zone at the surface. The water equivalent of a cubic foot (or of some smaller unit) of the snow will here be of the utmost significance.

We are still without proper studies of irradiation, not only from the various types of surface of the inland-ice, but from the frozen sea-ice off its borders. Comparative studies are needed of the radiation from inland-ice, from sea-ice (pack-ice or floe-ice), from sea water, and from land both with and without a snow-cover.

Amount of sublimation and its distribution. — It is of the utmost importance also to measure the amount of separation as snowflakes or ice-crystals from the lower air layers, since this appears to be the principal form of nourishment of the continental glaciers. The geographical limits for this process should be determined and their relation fixed to the area of downdraft in the anticyclone. The relative separations during day and night and, so far as possible, of the season, should also be studied.

Comparative studies about the margin of the area of strong radiation. — In view of the observed sharp boundary to the inner region of strong radiation upon the inland-ice of Greenland (see p. 117), comparative studies should be carried out on both sides of this border line specially as regards: (1) slope of surface, (2) air humidity, (3) air content of snow, and (4) nature of snow as regards fusion. Equally, if not more, important will it be at and near these crucial localities to investigate the overlying air, not only near the surface, but at considerable heights above it. Aërological studies above the inland-ice must be attempted and a technique worked out. Probably the most promising line of aërological research adapted to this special field is that with use of the aëroplane, already employed with success in Germany, England and Holland in aërological studies. It is also highly probable that if the time can be so chosen as to secure good visibility, sounding balloons or pilot balloons carrying meteorographs[19] can be sent up to moderate heights with a fair chance of recovery.

Drift-snow and the shaping of the ice-dome. — It has been seen how vast is the quantity of drift-snow that is carried out from the interior of the inland-ice and either piled up about its borders, deposited within the lower portions of sluice-ways, or dissipated upon the surface of the sea. It is highly desirable,

[19] S. P. Fergusson, "New Aerological Apparatus," *Month. Weath. Rev.*, vol. 48, 1920, pp. 317–322.

though during the great storms very difficult, to measure the quantity of drift at different heights above the ice. It is considerably easier to determine the thickness of the annual layers of snow deposit, and these should be measured at a considerable number of stations along a transection of the inland-ice, and careful study should be made of the surface before and after a heavy stroph of the anticyclone. Here within the slope areas of the ice domes there is offered the possibility of measuring accurately the amount of deviation of outflowing surface winds through the angles which the *sastrugi* make with slope lines.

Measurement of ice-flow within marginal region. — Intimately connected with the problem of distribution of the drift-snow is the measurement of the rate of flow of the ice itself within the marginal portions of the glacier. Such measurements have already been made in glacier outlets, but not as yet to any extent upon the inland-ice itself. The rate at which this velocity falls off with the distance within the ice-border remains to be determined. If nunataks are generally made use of for fixed stations of the theodolite, then as these rock masses affect materially the rate of ice-flow within their neighborhood, many measurements will have to be made to determine the law which controls the ice-flow. There is here an entirely new field to be exploited; for, quite without warrant, glacialists have generally assumed an outward motion throughout the mass of inland-ice. It is highly probable that this motion ceases at rather moderate distances within the ice-border.[20]

Aërological observations over the inland-ice. — The most promising line of attack upon the newer problems of the anticyclone is evidently quite largely to be made from the air above, and mainly *over,* not *outside,* the ice-domes themselves.

[20] W. H. Hobbs, *Bull. Am. Geogr. Soc.,* vol. 43, 1911, pp. 655–656. See also *Earth Features and Their Meaning,* Macmillan Co., 1912, pp. 302–303.

In the future meteorological stations must be established on, as well as near, the inland-ice. All such stations should if possible have their altitude determined by the precise methods of the spirit-level and be connected by radio.

Synchronized observations. — From now on the aim must be not so much to interpolate the so-called systematic observations which are made at widely separated stations, but to synchronize the observations of stations chosen with special reference to the system of inland-ice circulation, and in such a way that when a great stroph is in process of evolution above the inland-ice, it shall be possible to determine what is going on at all points within the system *at a particular instant* — how the surface air over the ice-slopes is moving, how far beyond the margin its influence is felt, how much of the extra-marginal air is being overridden, how the clouds in the upper levels are directed, and just how the approaching cyclones are being modified.

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